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# Renewable Energy Scenarios for the Kingdom of Saudi Arabia

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October 2008

Tyndall Centre for Climate Change Research Working Paper 125

**Renewable Energy Scenarios for the Kingdom of Saudi Arabia**

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**Tyndall Working Paper 125, October 2008**



**Abstract**

A widespread enthusiasm has been growing with regard to the transition towards more sustainable systems of production and consumption in order to meet today's needs without compromising those of future generations. Renewable energy technologies, in particular, are becoming internationally recognised as a vital contribution towards a sustainable energy future. This paper presents a set of renewable energy scenarios for the currently oil-rich Kingdom of Saudi Arabia. These scenarios have been developed using the Delphi technqiue, and represent a joint creation of thirty-five highly informed individuals from diverse backgrounds.

**Keywords**

Foresight Scenarios, Delphi Technique, Renewables, Sustainable Energy Policy, Saudi Arabia.

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## List of Abbreviations

| | |
|---|---|
| ASPO | Association for the Study of Peak Oil |
| CCS | Carbon Capture and Storage |
| CDM | Clean Development Mechanism |
| $CO_2$ | Carbon Dioxide |
| CRIEPI | Japanese Central Research Institute of the Electric Power Industry |
| CSP | Concentrated Solar Power |
| CTL | Coal-To-Liquids |
| DLR | German Aerospace Centre |
| FAO | Food and Agricultural Organisation of the United Nations |
| EIA | Energy Information Administration |
| GDP | Gross Domestic Product |
| GE | General Electric |
| GHG | Greenhouse gas |
| GW | Giga-Watt |
| IEA | International Energy Agency |
| IPCC | Intergovernmental Panel on Climate Change |
| $km^2$ | Square kilometre |
| kW | Kilo-Watt |
| kWh | Kilowatt-hour |
| mbd | million barrels per day |
| MENA | Middle East and North Africa |
| MW | Mega-Watt |
| OPEC | Organisation of the Petroleum Exporting Countries |
| O&M | Operation and Maintenance |
| PV | Photovoltaic |
| R&D | Research and Development |
| TW | Tera-Watt |
| UNDP | United National Development Bank |
| USD | United States Dollar |
| WTO | World Trade Organisation |

## 1. Introduction

Remarkable diversifications in terms of energy sources and the intensification of deploying renewable energy options are evident around the world. Such endeavours are, on the whole, fuelled by a range of environmental, energy security and/or economic considerations. Indeed, it is no exaggeration to suggest that the world is progressively undergoing transition from a hydrocarbon-based economy to one based on sustainable forms of energy. It is notable, however, that there has been comparatively limited interest in examining the prospect of renewable energy in major oil-producing countries, especially in those characterised by heavily oil-dependent economies. Consequently, there has been a corresponding dearth of research. Not only do these countries need to consider such sustainable energy means to further secure their energy and economic futures, but the potential key role that these countries could play in achieving a healthier future for generations to come should not be overlooked. In this regard, an instructive case to consider is that of the principal oil superpower, the Kingdom of Saudi Arabia. With at least a quarter of the world's proven oil reserves, it is also an increasingly urbanised and industrialised nation that is blessed with abundant solar radiation and a reasonable wind resource. Nevertheless, despite its several - yet somewhat tentative - undertakings in the field of renewables since the 1970s, its massive renewable energy resources have not yet been sufficiently exploited (Al-Saleh, 2007).

A substantial number of 'energy scenarios' have been developed around the world in order to provide a framework for the systematic explortation of energy perspectives (i.e. various possible combinations of energy options) and their potential implications. Many of these exploratory scenarios - which are quite often developed by means of the Delphi technique - aim to identify future opportunities and/or probable threats so that better-informed action can be taken today. The aim of this paper is to present a set of renewable energy scenarios, developed for the Kingdom of Saudi Arabia up to the year 2050, with the anticipation of provoking conventional thought and further stimulating constructive debate on the subject at both academic and policy level. Firstly, succinct overviews of scenario analysis and the adopted Delphi approach are provided. Following this, the design of this Delphi study and the development of the scenarios framework are explained. The paper then discusses the scenarios' qualitative assumptions (i.e. their narratives) and presents their quantitative implications.

## 2. What are Scenarios?

The roots of the scenarios are essentially as old as the human process of making sense of the world (i.e. planning, thinking about possibilities and reflecting on how the world works). In pioneering the development of scenarios for strategic military planning, Herman Kahn - regarded by many, including Cooke (1991), as ‘the father of scenario analysis’ - assumed that the future is somewhat predictable, otherwise there would be little point in planning (Kahn, 1960; Kahn and Wiener, 1967). He is also acknowledged for recognising that ‘predict and control’ methods of forecasting often do not serve organisations well. Van der Heijden (1996) reviewed the adoption of scenarios in Shell’s business planning from the mid-1960s. Supporting the views of Kahn, André Bénard - a former Managing Director of Shell - asserts that “experience has taught us that the scenario technique is much more conducive to forcing people to think about the future than the forecasting techniques we formerly used” (pg. 18). Besides their use in business planning, scenarios have been widely adopted by planners and decision-makers in an increasing number of fields and disciplines around the world (e.g. Davis, 2002; Kleiner, 1996; Ringland, 1998). Extensive reviews of previous energy scenarios are abundant in the energy literature (e.g. Harmin et al., 2007; Martinot et al., 2007; Nakićenović, 2000). Since energy infrastructure usually takes a very long time to build, most of the energy scenarios tend to adopt a very long-term perspective; i.e. looking ahead at least thirty to fifty years.

Apparently, various definitions have been put forward for the term ‘scenario’, which has been regarded as a “fuzzy concept that is used and misused, with various shades of meanings” (Mietzner and Reger, 2004: 50). For example, Godet and Roubelat (1996) defined a scenario as “a description of a future situation and the course of events, which allows one to move forward from the original situation to the future” (pg. 166). Another definition - perhaps cited more often - is provided by Parry and Carter (1998: 149) is “a coherent, internally consistent and plausible description of a possible future state of the world”. Simply put, IPCC (2000), in its *Special Report on Emissions Scenarios*, outlines that “Scenarios are images of the future, or alternative futures” (pg. 62). Moreover, scenarios are neither predictions nor forecasts, although attempts have been made in the past to predict (or forecast) the future as accurately as possible on the assumption that a particular outcome is most likely to occur. Mietzner and Reger (2005) maintain that the oil crisis of 1973 had an effect on futures research, through changing the paradigm of such research from ‘forecast’ to ‘foresight.’ Unlike forecasting, foresight scenarios do not describe just one future, but rather consider multiple possible futures as a way of coping with uncertainties. A review of the foresight literature also suggests that types of scenarios could be classified in different ways, such as quantitative-qualitative (IPCC, 2000); trend-peripheral (Ducot and Lubben, 1980); forecast-backcast (Dreborg, 1996); exploratory-anticipatory (Godet and Roubelat, 1996); predictive-explorative-normative (Börjeson et al., 2005); intuitive-formal and simple-complex (Van Notten et al., 2003).

Generally speaking, however, scenarios are mainly concerned with ‘What if?’ questions, and are designed to give representations of possible futures. Typically, future scenarios include a narrative component as well as quantitative illustrative indicators (Berkhout et al., 2001). Today, planners and researchers develop and build scenarios in several ways (e.g. Börjeson et al., 2005; Bradfield et al., 2005; Greeuw et al., 2000; Lindgren and Bandhold, 2003; Ringland, 1998). Current approaches, however, tend to emphasise the exploratory and creative elements of scenario development, as well as the need to involve diverse stakeholders in the process of scenario building. Berkhout and Hertin (2002) summarised the assumptions underlying these approaches as follows:

- The future is not only a continuation of past trends and dynamics; but can also be shaped by human choice and action.
- The future cannot be foreseen; but exploring the future can inform the decisions of the present.
- There is not only one possible future. Uncertainty and ignorance call for a diverse set of future scenarios mapping a ‘possibility space’.
- Developing scenarios involves both rational analysis and subjective judgement. It therefore requires interactive and participative methods. Users of scenarios must participate in their generation and evaluation.

Adoption of a Delphi approach – introduced in the next section – emerges as a practical and potentially powerful method for developing such scenarios.

## 3. An Overview of the Delphi Approach

In modern times, Dalkey and Helmer (1963) are often acknowledged for publicly portraying the Delphi technique – used by the RAND Corporation – as an interactive group process in order to bring together expert opinions on a particular issue. The Delphi technique is especially suitable for gaining subjective - yet informed - consensus on complex matters where precise information is limited or unavailable (Linstone and Turoff, 1975; Sackman, 1975). Loveridge (1999) further explains that the Delphi technique is an expert-based method of eliciting, collating and refining anonymous group judgements on a complex subject typically through circulating a number of sequential questionnaires (or rounds). In other words, it is a multi-stage approach, with each stage (i.e. a Delphi round) building on the results of the previous one. Repeat rounds of this process are carried out until an overwhelming consensus of opinion is reached. A review of the literature reveals that the Delphi technique has been extensively used within the realm of foresight (e.g. see. Breiner et al., 1994; Georghiou, 1996; Kuwahara, 1999). This is largely attributed to its suitability to cope with a high degree of uncertainty and its potential ability to address very complex issues. Examples of recent key energy scenario studies that have utilised the Delphi technique include those of Glenn and Gordon (2006), Wehnert et al. (2007) and the World Energy Council (2007). Despite its attractiveness however - as is the case with almost all research methods - some limitations are associated with the use of the Delphi approach. Most of the criticisms levied against the Delphi technique concern the make-up of the Delphi expert panel (Barnes, 1987; Kuusi, 1999).

To begin with, it should be noted that decades of debate over an agreed definition for the term ‘experts’ have not yet produced a definite answer; how an expert is defined remains largely a subjective endeavour (Armstrong, 2001; Linstone and Turoff, 1975). Definitions captured from the Delphi literature by Keeney et al. (2001) range from ‘specialists in their field’, ‘a group of informed individuals’ or ‘individuals who have knowledge about a specific subject’. After scrutinising over 150 Delphi studies, Sackman (1975) however expressed his reservations about the usefulness of ‘experts’ and tentatively argued the potential benefits of using ‘non-experts’. Goodman (1987) went further to argue that “it would seem more appropriate to recruit individuals who have knowledge of a particular topic and who are consequently willing to engage upon it without the potentially misleading title of ‘expert’” (pg. 732). Here, it might be reasonable to suggest that the commitment of participants is directly related to their interest, as well as to their potential input and involvement with the issue addressed in the Delphi study. In addition, several scholars (e.g. Delbecq and Van de Ven, 1975; Row, 1994; Moore, 1987) have emphasised the importance of the heterogeneity of the Delphi panellists, i.e. they are characterised by varying backgrounds, personalities and perspectives on the problem. It is believed that the diversity of the Delphi panel membership ensures a wide spectrum of opinions and judgements, thereby limiting a potential source of bias. Moreover, there seems to be little agreement in the literature about the ideal size of a Delphi panel. Whilst there appears to be limited empirical evidence with regard to the effect of the number of panellists on the validity or reliability of the consensus processes, many presume that the more participants there are in the Delphi panel, the better (Murphy et al., 1998). Such a perception seems to be largely down to the fact that the rationale behind the Delphi technique is, in fact, based on the old adage 'two heads are better than one' (Parenté et al., 1984). Nevertheless, it is notable that the Delphi technique does not typically require panellists to be a 'representative sample' for statistical purposes. Usually, the emphasis tends to be placed upon the qualities, expertise and relevance of the Delphi panellists as opposed their number, which is essentially influenced by factors related to the scope as well as to the resource constraints associated with the Delphi study itself (Powell, 2002; Spencer-Cooke, 1989). It is, however, interesting to note that whilst Turoff (1970) suggested a suitable panel size of anywhere between ten and fifty, many have actually proposed an optimum panel size of up to twelve people (e.g. Cavalli-Sforza and Ortolano, 1984; Phillips, 2000). Linstone (1978) argued that an appropriate minimum is seven panellists. Nevertheless, despite noting that many pioneering studies used very small panels, he reported Delphi panels comprising a few hundred and a Japanese Delphi panel "involving several thousand people" (pg. 274).

## 4. Delphi Study Design

The Delphi panel used in the study under consideration initially comprised thirty-five members, including some of the world's leading experts on the subject, as well as highly-informed Saudi specialists and stakeholders from both academia and industry. In essence, the developed scenarios are the joint creation of a wide range of individuals, and thus go beyond the assumptions and perspectives held by any interest group or individual (including that of the

Author himself). As a customary honorarium for participation, the panellists were offered the opportunity to have their names divulged as ‘Study Contributors’. Nevertheless, some of the participants, including high-profile Saudi officials, were not willing to have their names made known. This might be because of the sensitive nature of the subject of alternative energy in such a major oil-producing country. Appendix A lists the names of those contributors who did not mind disclosing their names, and Figure 1 demonstrates the backgrounds of the total body of participants. It should be noted here that panellists who work in the Saudi public and private sectors are included in the ‘industry category’. Only a few Saudi academics were found, mainly owing to the fact that the subject of renewable energy is not yet sufficiently incorporated in the teaching curriculum of Saudi universities.

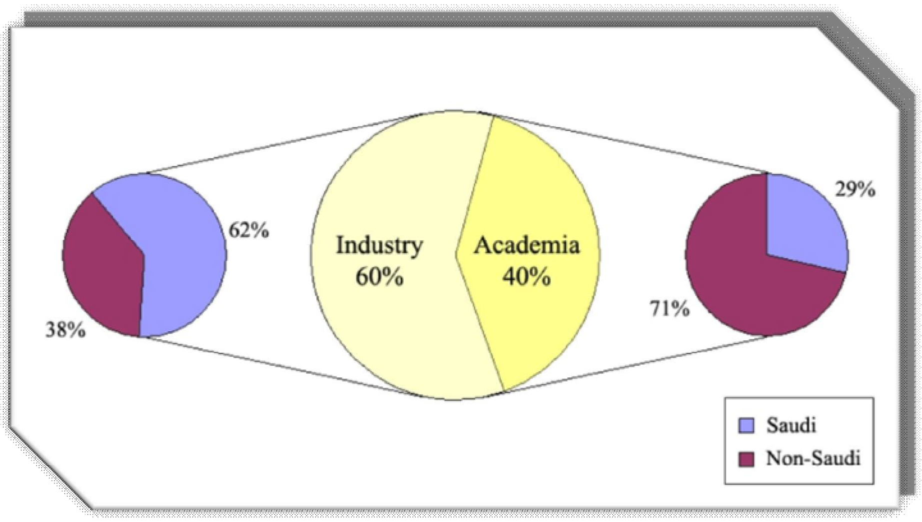


**Figure 1: Backgrounds of the Delphi Panellists**

In total, this study lasted for seven months and comprised three ‘formal’ Delphi rounds as well as several other ‘informal’ communications between rounds with some of the panellists whenever there was a need for further elaboration and/or additional information. The first round was devoted to giving the Delphi panellists a brief introduction to the purpose of this study as well as a detailed account of the procedure of scenario-building and the classic assumptions underlying the Delphi approach. They were also presented in the first round with a list of ‘scoping questions’. These questions started by actually asking the panellists to specify (and justify) whether or not they personally believed that renewables would have a major role to play in Saudi

Arabia by 2050. In addition, according to their preference, they were asked to rank and justify a number of energy technologies and potential key factors when considering the energy future for Saudi Arabia; they were also invited to suggest others. The second round reported on the results of the first round, and the panellists were also invited to comment on, elaborate upon or modify their original opinions. In addition, the second Delphi round posed further detailed questions concerning the future of the Saudi economy and of the power sector, which eventually helped to generate rich data for developing the renewable energy scenarios for Saudi Arabia. The last round configured participants' informed views, and made use of an extensive literature survey, in the form of a prototype set of scenarios for renewable energy supply in Saudi Arabia through to 2050. These prototype scenarios were subsequently made available for panellists' scrutiny. Throughout the Delphi study, the panellists were repeatedly encouraged to express freely their personal judgements and informed opinions (i.e. to agree or disagree with the reported mainstream view) in an absolutely anonymous environment where no view was perceived as being 'right' or 'wrong'. Of the thrity-five Delphi consultees, thirty-three responded to the first round, twenty-seven responded to the second round, and thrity-two responded to the third round. This could, in fact, be considered as an outstanding response given the low response rates and high attrition (i.e. drop-outs between rounds) rates recorded in the Delphi literature (e.g. McKenna, 1994; Mullen, 2003). Whilst there appear to be no firm rules for deciding when a consensus is reached, offering an interpretation of the meaning of consensus is an important factor that is often overlooked in most Delphis (Powell, 2002). In this particular Delphi study, consensus is defined as being the opinion held by over three-quarters of the participating Delphi panellists.

## 5. Developing the Scenarios Framework

Most scenario studies (especially those of an explorative nature, like this study) have adopted an approach in which a list of key factors is initially compiled. Next, the most 'significant' and 'uncertain' factors are pointed out. These factors (or variables) then represent the main axis along which scenarios differ and are characterised. In this Delphi study, the three factors that have consistently emerged as being both highly uncertain and very significant as regards the future of renewables in Saudi Arabia - are as follows:

- The availability of fossil fuels (in Saudi Arabia)
- Action on environmental protection (in Saudi Arabia and globally)
- Perception with regard to renewables (in Saudi Arabia)

Below is an analytical framework, based on these findings, for developing eight renewable energy scenarios (or alternative images of the future of Saudi Arabia). It should be noted that (P) refers to a positive perception of renewables in Saudi Arabia, whilst (N) refers to a negative one.

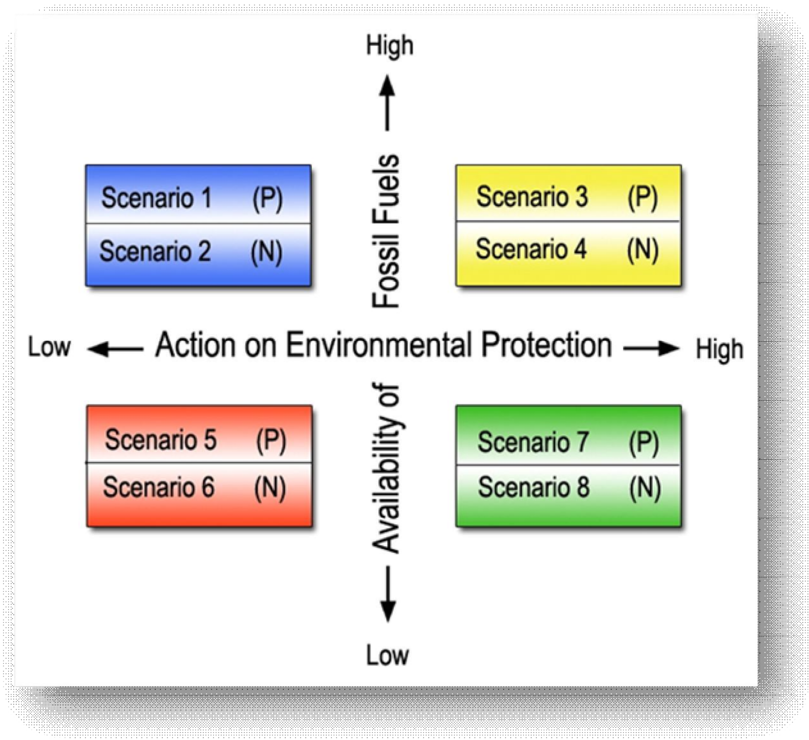


**Figure 2: Analytical framework for the scenarios**

Previous scenario studies suggest that people find it difficult to follow more than four scenarios. It was therefore decided to shrink the number of scenarios by grouping them into four scenario groups that incorporate four different narratives or storylines, but with eight distinctive quantitative parts. In order to facilitate later reference, the four group scenarios are differentiated in terms of colours. For instance, Green Scenarios (i.e. incorporating scenarios 7 & 8) could be seen as extreme 'images of the future' that assume a limited availability of fossil fuels and most stringent action to tackle environmental issues. In the Green Scenarios, it was assumed that Saudi Arabia would be contemplating a suite of renewable energy options (namely solar photovoltaics, solar thermal and wind power) in order to constitute 30% (or 45% in the case of positive perceptions) of the total power capacity installed in Saudi Arabia. For the remaining scenarios, however, it was decided to consider the prospect of a single renewable energy technology to provide 10% (or 15% in the case of positive perceptions) of the country's domestic needs.[1]

**Table 1: Summary of the developed renewable energy scenarios**

| Scenario Name | Scenario Number | Availability of Fossil Fuels | Action on Environmental Protection | Perception of Renewables | Renewables Target | Energy Technologies |
|---|---|---|---|---|---|---|
| **Blue** | 1 | **H** | **L** | **P** | 15% | Solar PV |
| | 2 | **H** | **L** | **N** | 10% | |
| **Yellow** | 3 | **H** | **H** | **P** | 15% | Solar Thermal |
| | 4 | **H** | **H** | **N** | 10% | |
| **Red** | 5 | **L** | **L** | **P** | 15% | Wind Power |
| | 6 | **L** | **L** | **N** | 10% | |
| **Green** | 7 | **L** | **H** | **P** | 45% | Solar PV, Solar Thermal & Wind |
| | 8 | **L** | **H** | **N** | 30% | |

**H** = High  **L** = Low  **P** = Positive  **N** = Negative

Below is a short account of each of the three aforementioned factors, followed by the criteria for choosing and allocating the energy technologies to the renewable energy scenarios.

## 5.1 Availability of Fossil Fuels

The future of the Saudi oil sector is undoubtedly as important to the world as it is to Saudi Arabia. Estimates of the size and importance of Saudi oil reserves differ according to the source.

[1] Following the mainstream view among the participating Delphi experts, the scenarios are to be developed for the sole purpose of meeting the demands of the domestic power sector. This should ultimately lead to freeing more oil and perhaps natural gas for export, thus boosting earnings for Saudi Arabia. It should be noted, however, that in Saudi Arabia, the power sector includes water as well as electricity. This is because most of the water used in the country is produced in desalination plants.

Whilst some sources in the literature maintain that Saudi massive oil reserves make up around 25% of the world's proven reserves (e.g. BP Amoco, 2006; EIA, 2005), there has been much scepticism on the part of a number of oil experts and some pseudo-scholars with regards to Saudi Arabia's current and future oil capabilities (e.g. Bakhtiari, 2006; Coxe, 2005; Roberts, 2005; Salameh, 2004; Simmons, 2005). In addition, it has been argued by the Association for the Study of Peak Oil that Saudi oil discoveries peaked in the 1940s whilst Saudi oil production is projected to peak in 2013 (ASPO, 2005). Whilst some suggest that Saudi oil production has already peaked, and the era of cheap oil has already ended, others maintain that a peak of Saudi oil production is still far away in the distant future. Whilst ambitious plans are - over and over again - announced for a massive increase of Saudi oil production capacity to 15 million barrels per day (mbd), many believe that Saudi oil production would peak at 12 mbd. Of course, one can easily end up reading the wrong things and listening to the wrong people on such controversial matters. The informed Delphi team, however, chose the factor of 'availability of fossil fuels' as being one of the most significant and uncertain factors when considering the prospects of renewables in the country.

### 5.2 Action on Environmental Protection

Whilst a number of environmental concerns were expressed with regard to the continued reliance on fossil fuels, the issue of global warming received most of the attention among the vast majority of Delphi panellists. Nonetheless, three of the Saudi panellists admitted their utter disbelief regarding the phenomenon of global warming, and further argued that no country should sacrifice its economic and industrial growth for the sake of reducing carbon dioxide ($CO_2$) emissions. As a group, however, they acknowledged the potential impact of and uncertainties sourrounding decisions and actions taken post-Kyoto (i.e. post-2012). For instance, questions were asked whether or not an international climate policy regime will come to fruition, with or without stronger national commitments to $CO_2$ reductions. Whilst admitting that it might be difficult to persuade the world community to commit to cutting the volume of $CO_2$, some strong views were expressed on the utility of existing carbon-trading systems, Clean Development and Joint Implementation Mechanisms, etc. It is believed that such issues would have tremendous effect on fuelling the momentum towards alternative energy means (such as renewables) in the whole world (including Saudi Arabia).

### 5.3 Perception of Renewables

The factors of ‘availability of fossil fuels’ and ‘action on environmental protection’ have initially provided a framework for four possisble renewables scenarios for Saudi Arabia. As highlighted in the Figure 2 and Table 1, the third factor - ‘perception of renewables’ - has further divided each of the four possible futures into either a scenario with ‘positive perceptions of renewables’, and hence a high renewables target, or a scenario with ‘negative perceptions of renewables’ and consequently a lower renewables target. The assumed factors that lead to either pathway are described below.

#### 5.3.1 Positive Perception of Renewables

Possible factors that could lead to a positive perception of renewables include an enhanced awareness of energy and environmental concerns as well as the setting of a range of financial incentives (such as net metering, feed-in tariffs and capital cost subsidies), that could boost the cost-competitiveness of renewables and probably lead to the creation of an additional market for on-grid applications. Another potential factor is the liberalisation of the energy sector and the honouring of the country’s commitments to the World Trade Organisation (WTO), leading to the removal of the heavy subsidisation of the prices of electricity and water, and eventually resulting in the promotion of energy-saving measures and the widespread use of renewables.

#### 5.3.2 Negative Perception of Renewables

On the other hand, scenarios with negative perceptions of renewables envisage a lack of popularity with regard to energy-saving measures on the demand side, a lack of efficiency improvements on the energy production side, a limited domestic awareness of energy and environmental issues and the relative absence of any financial incentives that could enhance the potential of renewables. Moreover, given the Government’s interest in keeping social and political tranquillity in the country as long as it has decent oil revenue, these scenarios related to a negative perception of renewables assume a longer continuation of a high level of consumer subsidies. As a result of these factors, the future demand for domestic power in Saudi Arabia is assumed to be higher than in the case of scenarios with positive perception of renewables.

### 5.4 Choice of Renewable Energy Technologies

A few panellists vigorously promoted the attractiveness of nuclear power for Saudi Arabia. Nevertheless, the mainstream view did not turn out to be in favour of nuclear power, not just because it is a non-renewable source of energy, but mainly owing to the existence of significant regional political reasons to avoid it. Moreover, a couple of the Delphi consultees argued (without proof) that since crude oil exploitation techniques and equipment are highly developed in Saudi Arabia, there might be a potential for a geothermal solution that could deliver its full capacity round the clock independent of the rough climatic conditions of the country. Throughout the Delphi study, however, solar photovoltaics (PV), wind power and solar thermal power (i.e. Concentrated Solar Power 'CSP'; Parabolic Trough Technology) have undoubtedly emerged as the most preferred renewable energy technologies in the case of Saudi Arabia. In terms of lifecycle greenhouse emissions, many previous studies have concluded that solar thermal power compares favourably with wind and solar PV (e.g. see Kuemmel et al., 1997; Pehnt, 2006). Bearing in mind its environmental attractiveness, solar thermal power is allocated to the scenarios with 'high' action on environmental protection (i.e. the Yellow Scenarios). In terms of lifecycle energy demand, since manufacturing wind turbines is not as energy-intensive as the production of solar (silicon-based) PV panels, wind power is assigned to scenarios where there is a limited availability of fossil fuel-based energy (i.e. the Red Scenarios).

### 5.5 Scenarios as Caricatures

The above brief justification for assigning renewable energy technologies to the different scenarios is not - by any means - comprehensive, as there are many conflicting considerations when it comes to the controversial dilemma of contrasting various renewable energy technologies. For instance, when compared with solar power, one might argue that wind power could potentially have a big impact on the environment owing to the visual effects, bird deaths, noise, etc. associated with the operation of wind turbines. Moreover, despite a number of previous experiments which have been fairly successful, some experts still argue that PV panels would never withstand the harshness of Saudi Arabia's deserts. One might further argue, and rightly, that the total land requirement (per unit of generated electricity) is much higher for wind power than is the case for solar PV. Nevertheless, whilst PV farms replace a natural ecosystem, wind farms are somewhat compatible with other land uses. On the other hand, conventional fossil-based energy generation does not require as much land use because these energy sources have very high energy densities and are usually extracted from beneath the earth's surface. Given the fact that Saudi Arabia is a large country with a relatively low population density (95% of its land area is unpopulated desert/relatively cheap landscape), however, a substantial number of participating experts argued that the significance of the land requirement factor might not be of such great importance as in other parts of the world.

Without going into further detail on the positive potentials and/or negative impacts associated with the various renewable energy technologies, it is perhaps important to emphasise here that it is unlikely that a single renewable energy technology will be an ideal worldwide source of power generation because each of these technologies is (or soon will be) better suited to play an important role in supplying major portions of the energy mix in particular world regions. Whilst it would be unwise for any country to 'put all its eggs in one basket' and ultimately rely on any one energy form, assignment of different renewable energy technologies to the identified scenarios was carried out in order to generate a range of dissimilar 'quantified' outcomes for the scenarios. It is worth mentioning here that many exploratory energy scenarios adopt a more holistic energy system analysis; e.g. they look at the prospect of the same set of technologies with various renewables shares in the overall energy system. Given, however, that a scenario study of this nature and scale is the first of its kind in Saudi Arabia, and since the central aim here is to stimulate discussion about the potential of renewables in the country, most of the Delphi panellists favoured allocating dissimilar renewable energy technologies to the different scenarios. Such a technology allocation and the assumed constant renewables shares for the developed scenarios were therefore not adopted for the purpose of comparing and/or favouring certain types of renewable energy technologies.

What should also be remembered is that when we build scenarios based on the most significant and uncertain factors, comparison of scenarios in terms of 'likelihood' or 'plausibility' is not really relevant because the narratives of these scenarios (not necessarily their assumed technologies) represent rather extreme 'equally plausible' views of the future. The basic assumption underlying this approach is that, by focusing on extreme cases, one can have a chance to explore the full range of uncertainties deriving from the most significant factors. In fact, it is most likely that the future will be a combination of the eight scenarios as, to some extent, each scenario's narrative has elements of plausibility. In addition, a number of influential factors (other than the three considered) could emerge over time and they could pull the energy future of Saudi Arabia in entirely different directions. So, as argued by the Energy Futures Task Force (2001) and Virdis (2003), the strength of developing such contrasting scenarios does not lie in the accuracy of any of the scenarios per se, but rather in the insight gained from highlighting possible choices and the implications of one scenario and how these differ from those of other scenarios. In this regard, exploratory scenarios are always claimed to be neither a wish to be attained nor a prediction, but a representation of possible future pathways.

Finally, it is imperative to recognise that developing any set of scenarios would essentially involve many assumptions as well as the introduction of an unavoidable element of simplification. For instance, scenario-building implies the assumption that some factors remain constant, and that other factors develop over time consistently in the direction of the chosen variables. The Blue Scenarios, for example, assume that action on environmental protection remains limited over the long period of the scenario horizon (i.e. up to 2050). In reality, this would not entirely be the case as each driver is likely to show differing intensities and direction over this long period of time. Such oversimplification should therefore be borne in mind when we examine the implications of the scenarios, but should not detract from the utility of the analysis.

## 6. Common Assumptions for all Scenarios

Whilst the developed scenarios vary in terms of the availability of fossil fuels, action on environmental issues and the perception of renewables, it is assumed that they share the following common features.

### 6.1 Population of Saudi Arabia

After the averaging of data provided by the American Census Bureau, the Central Intelligence Agency, the Foreign and Commonwealth Office, the Saudi Ministry of Economy and Planning, the United Nations Development Programme 'UNDP' and the World Bank, the population of Saudi Arabia - towards the end of the year 2006 - is estimated to be 25.6 million. The following table lists some estimates – obtained from the literature – on the recent annual growth rates of population in the Kingdom of Saudi Arabia.

**Table 2: Annual rates of Saudi population growth as quoted in recent literature**

| **Source** | Aarts (2004) | FAO (2004) | Heradstveit & Hveem (2004) | IEA (2005) | UNDP (2006) |
|---|---|---|---|---|---|
| **Annual Population Growth** | 3.4% | 2.9% | 3.5% | 2.7% | 4.1% |

Bearing in mind that "no single right projection can be deduced from past behaviour" (Wack, 1985: 73), the current rate of Saudi population growth is 'conservatively' assumed by the research participants to be 3% per annum. Moreover, whilst Saudi growth rate has not always been steadily decreasing with time (Cordesman, 2003), it is assumed that this rate would gradually fall to 1.5% in 2050 as a result of more women starting to work and the probable launch of population rationalisation programmes. Based on these assumptions, the following graph demonstrates the expected growth of the Saudi population until 2050.

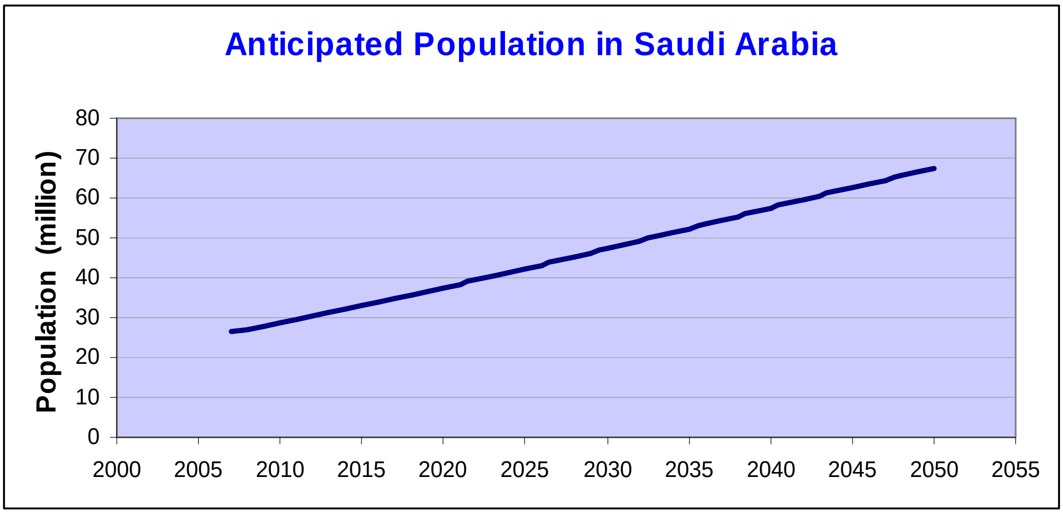


**Figure 3: Anticipated Saudi population through to the year 2050**

## 6.2 Required Future Power Capacity in Saudi Arabia

Future demand for electricity and water in Saudi Arabia is set to grow owing to a rapidly-growing population, increasing urbanisation and swift industrialisation. The next few pages detail the process of estimating future power demand and hence the required power capacity in Saudi Arabia, based on an intensive literature survey as well as informed inputs from many of the participating Delphi experts.

There are various (and often quite sophisticated) ways to estimate the future power demand for a given country. Many of these are based on models and formulae that take into account a wide range of factors, including potential population growth, economic and income growth, price/kWh, fuel prices, degree of urbanisation, future national plans, etc (see Munasinghe and Meier, 1993; Rhys, 1984). Whilst none of these methods is primed to have the ability to predict the future, each of them has its strengths and weaknesses; and their selection should be based on the availability of historical data and the purpose of the study. Bearing in mind that the focus of this current study is not really on economics or on precise predictions, some participating experts have suggested a simple way in which we could roughly estimate future demand for electrical power in Saudi Arabia, i.e. to multiply anticipated population by projections of electricity consumption per capita. An intensive literature review has therefore been conducted in order to determine the current and historical electricity consumption per capita in Saudi Arabia. Whilst no seemingly reliable historical data were found, a number of sources maintain that it is currently close to the European Union's average. The work by the German Aerospace Centre 'DLR' (2005) is probably one of the most comprehensive published studies on current and future demand for power in the Middle East and North Africa (MENA) region. Without taking into account the electricity consumed in desalination facilities, it estimates the annual electricity use per capita in Saudi Arabia to be around 5,800 kWh. Other available estimates - which account for desalination requirements - include those of the International Energy Agency 'IEA' (2005) and Toukan (2007). The average value of the latter two published estimates and an estimate obtained from a primary source of information is approximately 6,200 kWh/cap/year (i.e. 7% above the DLR's estimate). This may seem reasonable given that, according to IEA (2005), 10% of the total Saudi generation capacity installed in 2003 was reported to have been devoted to combined water and electricity production facilities.

Considering the future electricity use rate per capita in Saudi Arabia, one would expect that this might decline a bit over the years as more efficient equipment and appliances are put into use. Nevertheless, the issues of potential energy conservation and savings will be dealt with at a later stage. So, for the time being, assuming no energy conservation or efficiency improvements in Saudi Arabia, the growth rate of electricity consumption per capita is assumed to continue - owing to ongoing urbanisation and industrialisation - according to the historical trend at 5% per annum (Alajlan et al., 1997). It is assumed, however, that this growth will gradually level off around the year 2035 as most electric end-uses could be 'saturated' and hence a plateau of demand could be reached by that time. Whilst such saturation in electrical consumption growth may never take place, most of the participated experts voted for its likelihood in Saudi Arabia. Based on these conjectures, the projected electricity use per capita in the country would be as follows:

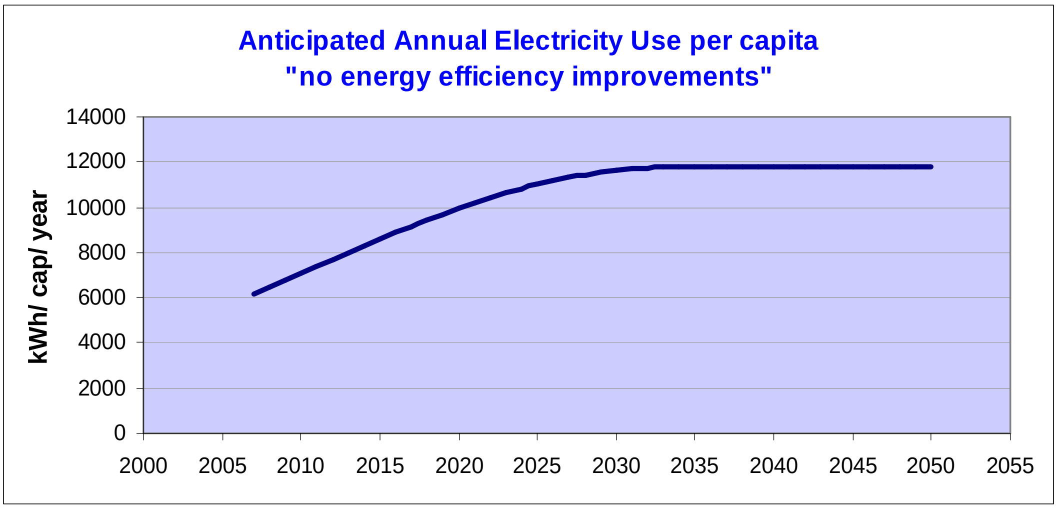


**Figure 4: Anticipated annual power use in Saudi Arabia (measured in kWh/cap/year)**

For comparison purposes only, the IEA's (2005) estimate - which presumably took into account potential energy savings efficiency and efficiency improvements - for the year 2030 is 10,600 kWh/cap/year. By multiplying the values shown in the above graph by the previously assumed population projections, the anticipated growth in electricity consumption in Saudi Arabia is as demonstrated overleaf.

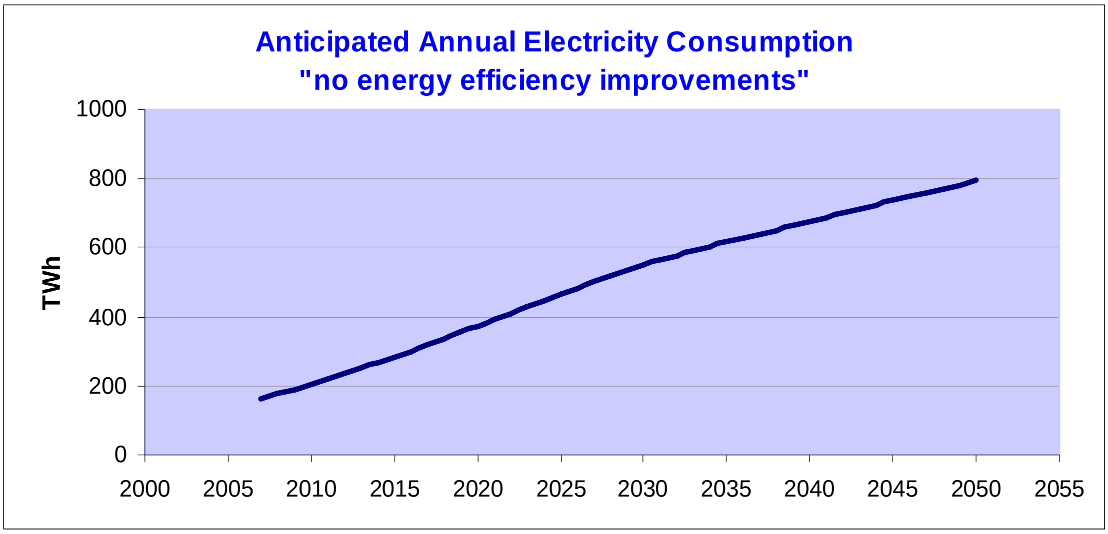


**Figure 5: Anticipated annual power consumption in Saudi Arabia (measured in TWh)**

According to data on the actual use of Saudi electricity in 2005 provided by the IEA (2008), the difference between reported electrical production and consumption is estimated to have been 23% in that year. Whilst this difference may seem somewhat on the high side, one of the participating informed experts commented that it is not very unlikely when given potential production losses and the distances involved with transmission and distribution in Saudi Arabia. In addition, there might be some statistical defects such as consumption that, for one reason or another, were not listed under the overall consumption figure, e.g. power consumption of the Saudi Electricity Company itself, or possibly electricity that is used in other sectors but provided for free. Another factor might be 'non-technical losses', i.e. power theft, which is a major issue in many developing countries, but possibly less so in Saudi Arabia.

For the purpose of this study, it was decided to assume a difference of 20% between Saudi electric production and consumption in order to account for all energy losses between the power plants and the end-users; these energy losses would, however, gradually decrease over the years and become 10% by 2050.

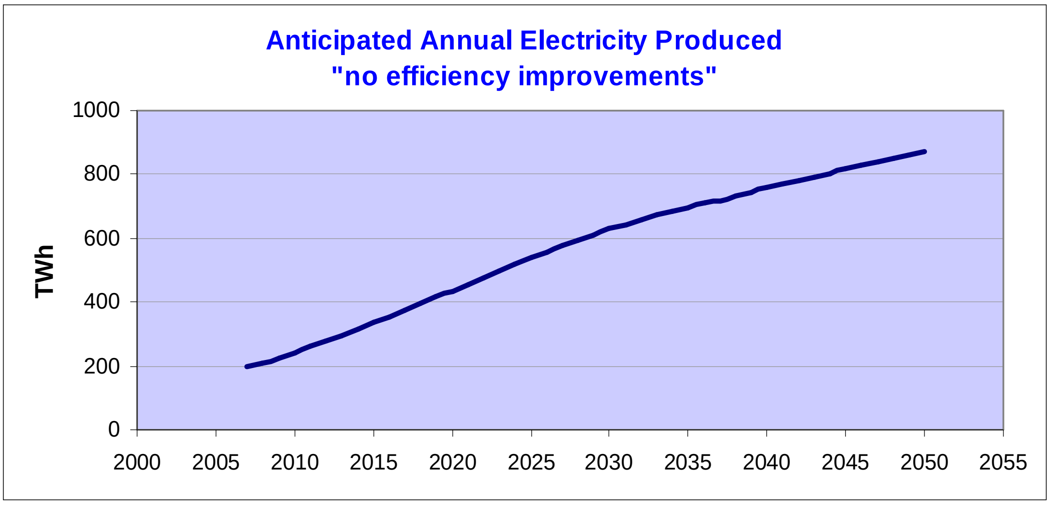


**Figure 6: Anticipated annual power production in Saudi Arabia (measured in TWh)**

In order to estimate the average power demand per annum (in GW), the values in the above graph had to be multiplied by 1,000 (to convert Terawatts to Gigawatts) and then divided by 8,760 hours (i.e. 365 days x 24 hours).

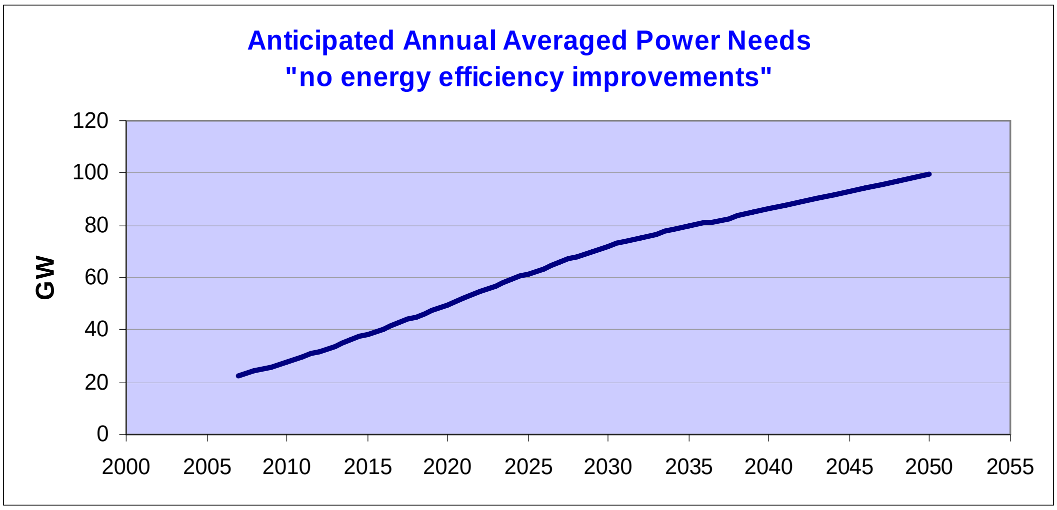


**Figure 7: Anticipated annual power demand in Saudi Arabia (measured in GW)**

Having broadly estimated the average electric power needed in Saudi Arabia every year until 2050, once can now estimate the required installed capacity in the future, and to which renewable energy options would contribute to varying extents in the different scenarios. Rotmans and Vries (1997) mentioned that the required installed capacity of a country equals the sum of national peak demand and national reverse margin, which is the amount of extra capacity the system must have for emergencies and planned outages. One way of estimating maximum peak demand is to assume a certain 'load factor'. This is essentially the ratio of average demand to the maximum peak demand. A system with a relatively high load factor means that the electric demand is consistent over time; thus the utility could operate more of its installed capacity profitably (Ellicott et al., 1998). Bearing in mind the substantial contribution of weather-related end-uses (e.g. air conditioning), one would expect a load factor that is considerably less than one. One of the Delphi consultees suggested that assuming a load factor of 64% and a reverse margin of 15% would be quite sensible for a country like Saudi Arabia. It appears, however, that it has been planned that 51% of future additions until 2030 (compared with 10% in 2003) needs to be devoted to combined water and electricity production plants (IEA, 2005). Since desalination is taking an increasing fraction of Saudi electricity use, one may expect the load factor to increase a bit because such desalination facilities would be likely to be operated around the clock. The Delphi therefore team assumed that the current load factor of 64% will gradually increase to 67% by 2050. Based on these assumptions which are made on an absolute theoretical level, Figure 8 anticipates the annual peak demand in Saudi Arabia through to the year 2050.

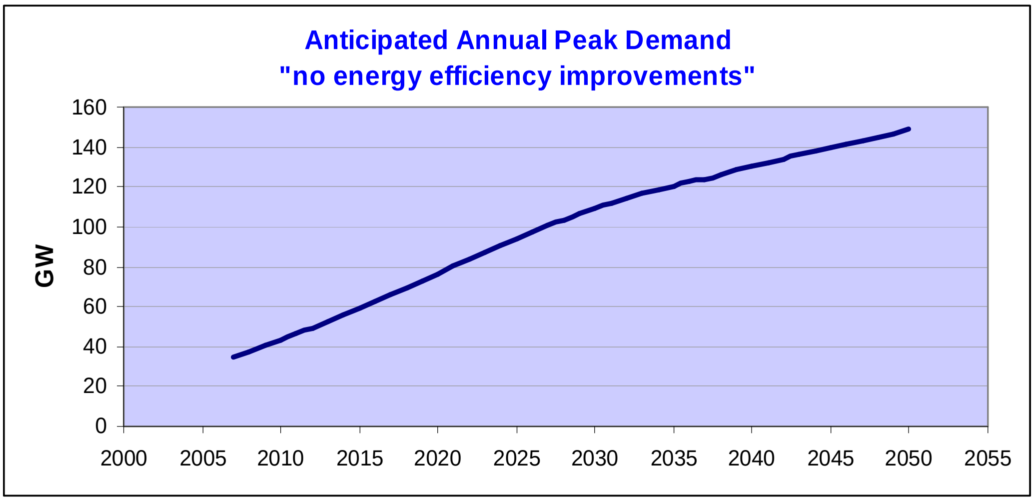


**Figure 8: Anticipated annual power peak demand in Saudi Arabia (measured in GW)**

Finally, some studies have argued that the rate of energy savings is not always correlated as neatly with final energy demand as it is with other factors such as economic growth (Anderson et al., 2005). Given that energy intensity is measured as units of energy per unit of Gross Domestic Product (GDP), Table 3 illustrates some of the assumptions adopted in some recent energy scenario studies regarding the potential implications of improved energy efficiency measures.

**Table 3: Implications of energy efficiency measures as assumed in recent scenario studies**

| Study | Assumptions |
|---|---|
| Greenpeace & EREC (2007) | Owing to assumed energy efficiency improvements under the 'Energy Revolution Scenario', energy intensity is anticipated to fall by around 70% between 2003 and 2050, whilst global energy demand in 2050 will be almost the same as that of 2003, despite economic growth |
| GWEC & Greenpeace (2006) | In the 'High Energy Efficiency Scenario', by 2030 global electricity demand would be 39% lower than in the 'Reference Scenario' |
| IEA (2006) | In the 'Accelerated Technology Scenario', energy-efficient technologies reduce global energy demand by 24% by 2050 |

For the purpose of this study, it is assumed that when energy savings and efficiency improvements are vigorously pursued, the actual energy demand, and hence the required power capacity in Saudi Arabia will be reduced. For instance, applying passive solar design in Saudi buildings should help to reduce the growing demand for active air conditioning. Owing to the previously assumed emphasis (in Section 5.3) on energy saving and conservation measures as well as the phasing-out of consumer subsidies in the case of scenarios with positive perceptions of renewables, the required power capacity in Saudi Arabia is assumed to decrease gradually, compared with scenarios with negative preferences for renewables. Alajlan et al. (1997) tentatively argued that if energy conservation measures are seriously considered in Saudi Arabia, at least 25% of the required power-generating capacity could easily be reduced within a few years. Whilst these rough estimates are a decade old, it is assumed here that it would be possible to achieve a 30% cumulative reduction of power capacity required in the country by the year 2050 in the scenarios with positive perceptions of renewables.

Thus, based on the above assumptions, the Figure 9 shows the estimated required power installations in Saudi Arabia for the scenarios of positive as well as negative perceptions of renewables.

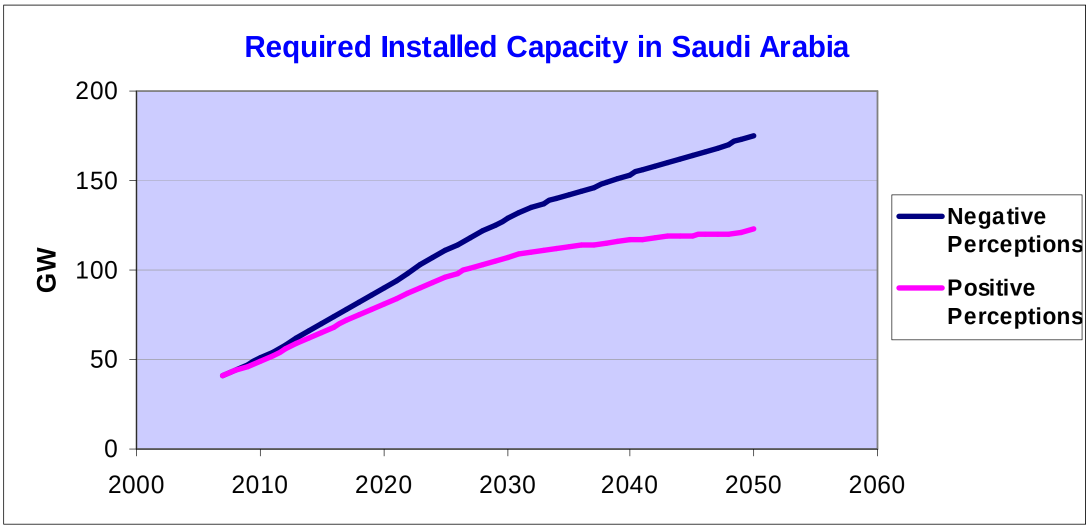


**Figure 9: Required Saudi power installations through to the year 2050 (estimated in GW)**

Indeed, especially in view of the unfortunate lack of consistent historical trends, the Delphi team was not looking for 'precision' in this fairly broad level of treatment. Nevertheless, an attempt has been made to check whether the above projections on the required future installations are fairly reasonable by comparing them with previous forecasts available in the literature. For instance, IEA (2005) forecasts that installed power is set to increase in Saudi Arabia to 102 GW by 2030, which is very close to the team's estimate for scenarios with positive perception of renewables (i.e. 107 GW). Whilst the IEA's estimate might not have been based on a potential 30% capacity reduction as a result of employing vigorous energy-saving measures and removing heavy consumer subsidies, it is based on a relatively higher current per capita electricity use (i.e. 6,790 kWh per year). A recent study by an Ireland-based consultancy firm has also projected similar future demand for power in Saudi Arabia through to 2015 (Research and Markets, 2008). Another key study is that of DLR (2005) whose projections through to 2050 largely follow the shape of the above curve for scenarios with positive perceptions. Nevertheless, the DLR's forecast of the required installed power capacity is comparatively low (i.e. 85 GW). An obvious reason is the fact that the DLR study is based on relatively lower population projections (i.e. their assumed annual population growth declines from 2.9% to 0.9% over the period 2007-2050).

### 6.3 Pace of Technological Change

It is assumed that all energy-related technologies will continue to develop in all scenarios, with higher efficiencies expected in the future. Such a technological change would not, however, be affected by the policies and actions of the Saudi leaders. Nevertheless, the rate at which an energy technology develops and penetrates the market varies across the scenarios. Broadly speaking, renewable energy technologies emerge strongly in scenarios with a positive perception of renewables, whilst their effective diffusion is adversely affected vis-à-vis the use of fossil fuel-based technologies in the remaining scenarios. It is assumed therefore that technological trajectories do not depend entirely on innovators (Geels, 2006; Schwartz-Cowan, 1987), but probably more upon adoption choices by users who are embedded in the demand domains (*cf*. Wolsink, 2000).

### 6.4 Other Issues

An underlying assumption in the developed energy scenarios for Saudi Arabia is that its oil supply is not going to be abruptly disrupted through the scenarios horizon owing to political instability in the Middle East region or security threats such as attacks on Saudi energy facilities and critical infrastructures. Moreover, all scenarios are developed on the assumption that Saudi Arabia is going to rely on imported 'foreign' renewable energy technologies to begin with (say until the year 2025), and then will consider indigenous development further down the line (around 2025-2050). Suggested factors that could contribute towards the successful establishment of indigenous renewable energy industries in Saudi Arabia include:

- Political support is quite often a key factor, especially so given the situation in the Kingdom of Saudi Arabia. As argued by one of the Delphi consultees, "In any monarchy, where authorities have considerable power and considerable financial resources, this situation is entirely controllable by the authorities, and thus is a policy choice"
- The move towards a more participatory system of governance, and improvements in terms of bureaucratic management and openness in governmental structures
- Strengthening the Kingdom's educational system and providing vocational training
- Enhancing coordination and links between Saudi universities and industry
- Allocating budgets to support the fields of science and technology, as well as widening R&D activity in both public and private Saudi sectors

- Buying into international energy companies which conduct a lot of R&D
- Market liberalisation in the Saudi power sector
- Increasing the role of the private sector in electricity and water projects
- Continuing to reform the investment climate in Saudi Arabia
- Developing a culture of patenting and entrepreneurship in Saudi Arabia
- Rewarding innovators and researchers in all relevant fields
- Setting up more technological and know-how transfer joint-venture programmes
- Hosting Clean Development Mechanism (CDM) projects
- Inviting leading renewable energy technology manufacturers into the country

## 7. Scenarios Narratives

Having introduced the context within which the scenarios will operate and the factors that are considered common to all the scenarios, it is now appropriate to present the renewable energy scenario sets for the Kingdom of Saudi Arabia in order to explore several alternative renewables pathways for the country through to 2050. These scenarios represent stories about the future, reflecting various assumptions about how current trends and issues will play out and about what other factors could potentially come into play to create a range of possible futures. It should be noted however that each narrative describes one of many different, yet equally plausible, futures for the country. Whilst each narrative is designed to be read and explored on its own, considering all of the scenarios will help to establish a better appreciation of a wide range of different energy futures for the country.

### 7.1 BLUE SCENARIOS

These scenarios represent what might be thought of as a continuation of current trends in terms of the abundant availability of fossil fuels and limited strategic actions on environmental protection. Nonetheless, owing to other factors, such as increasing domestic demand for energy as well as a desire to free hydrocarbon resources for export and - perhaps more importantly - petrochemical production, Saudi Arabia is considering the renewable energy option with which it is most familiar (i.e. Solar Photovoltaics). As previously mentioned, in the scenario with a positive perception of renewables, solar PV enjoys a relatively high penetration in on-grid applications as well (i.e. decentralised production of electricity).

In a world of abundant oil reserves, Saudi Arabia - as a major oil-producer with the greatest spare production capacity - could choose to maximise its oil production and perhaps further expand its operations in the Far East in order to achieve a maximum market share and ultimately become the world's unsurpassed supplier. As a result of the adoption of a sustained 'market flooding' strategy, oil prices could gradually drop down to as low as $10 per barrel. This low price may, however, guarantee the maintenance of reasonable revenue to Saudi Arabia, whose production costs are very low (according to some unofficial estimates perhaps as low as $1.5 per barrel at present). Such an aggressive approach - although regarded by a few panellists as being somewhat technically difficult - would result in driving other 'high-cost' oil-producers (including many OPEC members) from the market, as well as demolishing much of the global interest and research into alternative energy means (including renewables).

## 7.2 YELLOW SCENARIOS

These scenarios envision a future in which global environmental concerns become significantly stronger and environmental actions become more coordinated. Greenhouse gas emissions are vigorously scrutinised with performance targets being completely agreed on and respected around the world. Carbon Capture and Storage (CCS) has become a widely-adopted technology, and technological advancements in fuel cells and hydrogen storage are attributed to a strong market growth for hydrogen fuels in transport applications. As a result of environmental movements towards carbon-neutral and carbon-free technologies, the rate of climate change is slowed (yet not reversed). Given the availability of oil resources in Saudi Arabia, a 'market flooding' strategy that might drive oil prices down makes a lot of sense in a world where environmentally-friendly options are strongly favoured. Nevertheless, adopting such a hostile strategy, which Saudi Arabia has constantly avoided, would mean that maintaining good relations with other oil-producers could become an increasingly difficult challenge. For a country like Saudi Arabia that is blessed with very high levels of direct solar radiation, but is increasingly faced with an increased demand for electricity and water as well as a low revenue stream (owing to low oil prices), solar thermal seems to be an attractive choice worth considering.

## 7.3 RED SCENARIOS

The Red Scenarios depict a future that is characterised by rapidly-dwindling oil reserves combined with carelessness towards the tackling of environmental issues. There is an apparent lack of adequate commitment to reducing $CO_2$ with only a few residual emission trading schemes. Consequently, there is an increase in climate change migrations and natural disasters such as flooding. In a world of scarce oil reserves, Saudi Arabia - which has often been perceived as a 'consumer-friendly OPEC member' - could decide dramatically to cut its oil production in order to take economic advantage of the resulting 'skyrocketing' oil prices. If the steep-rising oil prices are sustained, they could easily have a disastrous impact on the global macroeconomy and financial markets as well as creating political/social chaos in large oil-importing countries. Nevertheless, this strategy does not just increase the near-term oil revenues of Saudi Arabia, but could also benefit other 'high-cost' oil-producers whilst ensuring that its rapidly-diminishing national asset is not being dissipated too quickly. With high oil prices and the non-existence of a carbon-constrained world, the development of tar sands and Coal-To-Liquids (CTL) could become viable (although not necessarily of great significance). Despite the absence of a vigorous environmental stimulus, high oil prices could motivate interest and research into alternative energy sources and thereby boost the global prospects for renewables, which are not being sufficiently encouraged by environmental arguments. Given its huge land area and its reasonable wind resources, Saudi Arabia could contemplate the option of wind power in order to boost the share of renewables in the country's energy mix.

## 7.4 GREEN SCENARIOS

The Green Scenarios share with the Red Scenarios the limited availability of fossil fuels. In the Green Scenarios, however, there is much more concern and urgency attached to environmental issues. The global concerns of greenhouse gas emissions would become the subject of intense negotiations and strict international agreements. The combined effect of these factors would consequently enhance the viability of renewables and non-fossil energy means (including nuclear power) around the world. Moreover, hydrogen and biofuels would become widely used as transport fuels. Following this trend, Saudi Arabia would be no exception in pursuing a range of renewable energy technologies (i.e. solar thermal, solar PV and wind power) in order to meet its rising domestic needs for electricity and water production. With regard to its remaining oil reserves, Saudi Arabia might decide to cut production and oil sales in order to stretch the lifetime of its most precious export and further expand its energy-intensive industrial capabilities. Consequently, the availability of a continuous flow of ‘cheap’ fossil fuels into international markets would become increasingly threatened. Oil-importers could therefore start to act independently to enhance their energy security, e.g. through supporting CTL and oil shale projects that would be coupled with CCS in order to avoid increased greenhouse gas emissions.

## 8. Quantitative Implications

For a full account of the adopted quantitative assumptions and calculations, please refer to Appendix B. It cannot be overstated that not only are the quantitative results based on simplified calculations, but they are also based on long-term cost forecasts which are subject to a substantial degree of error. In order to enhance the robustness of such results, a probability analysis using Monte Carlo simulation could have been conducted. Nonetheless, this option was soon disregarded because such analysis would be beyond the scope of this explorative study. The main reason for conducting these basic calculations is an attempt to make the developed scenarios more realistic, convincing and interesting for the small number of senior Saudi stakeholders to whom they are going to be presented. Thus, for the purpose of this study, it was decided that useful outputs for each scenario would be the following:

- The potential greenhouse gas (GHG) emission reductions.
- The potential savings of fossil fuels that would have otherwise been used for electricity-generation (expressed in terms of barrels of crude oil).
- Whilst the factor of land requirement might not be of great importance in the case of Saudi Arabia (with a total surface area of 2,150,000 $km^2$), it has been suggested by some

panellists that it could be of relevance to estimate the total area that the renewable power plants would roughly occupy in each scenario, especially given the anticipated increase of population and agricultural cultivation of land in Saudi Arabia.

- The net annual lifecycle costs/savings (i.e. averaged from the annual lifecycle costs/savings estimated for all nine pre-planned capacity additions through to the year 2050). These annual lifecycle estimates are essentially levelised figures based on an assumed discount rate and power plant lifetime, as well as a calculated net present value.

There is no intention ultimately to regard any of the eight developed scenarios as the best way forward for Saudi Arabia. Indeed, one of the points which this study demonstrates is the existence of a whole range of future pathways, all of which could have some favourable and/or unfavourable outcomes given a particular set of circumstances and assumptions. The following three figures show the potential implications of each of the developed scenarios in terms of total GHG reductions, fossil-fuel savings and land requirement (vis-à-vis a zero-renewables setting) over the set time horizon of 2050.

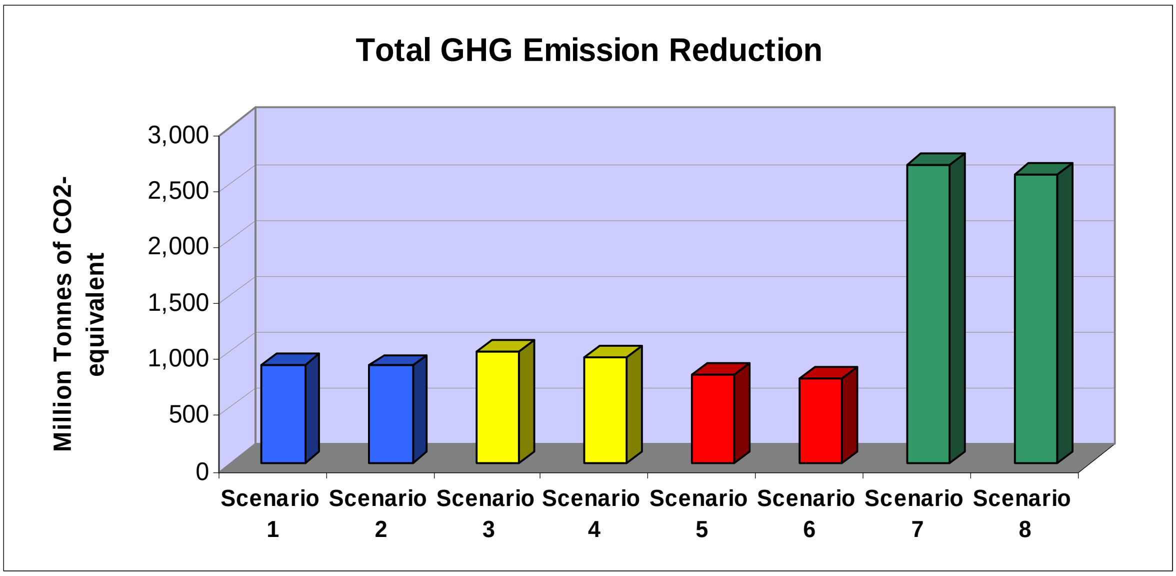


**Figure 10: Estimated total greenhouse gas reductions for the developed scenarios**

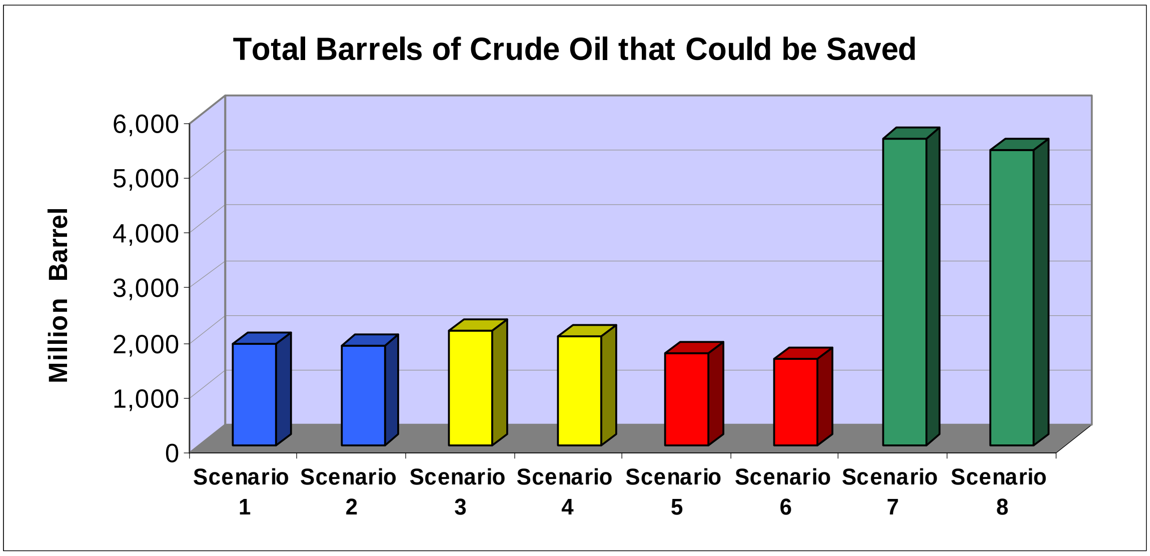


**Figure 11: Estimated total fossil fuel savings for the developed scenarios**

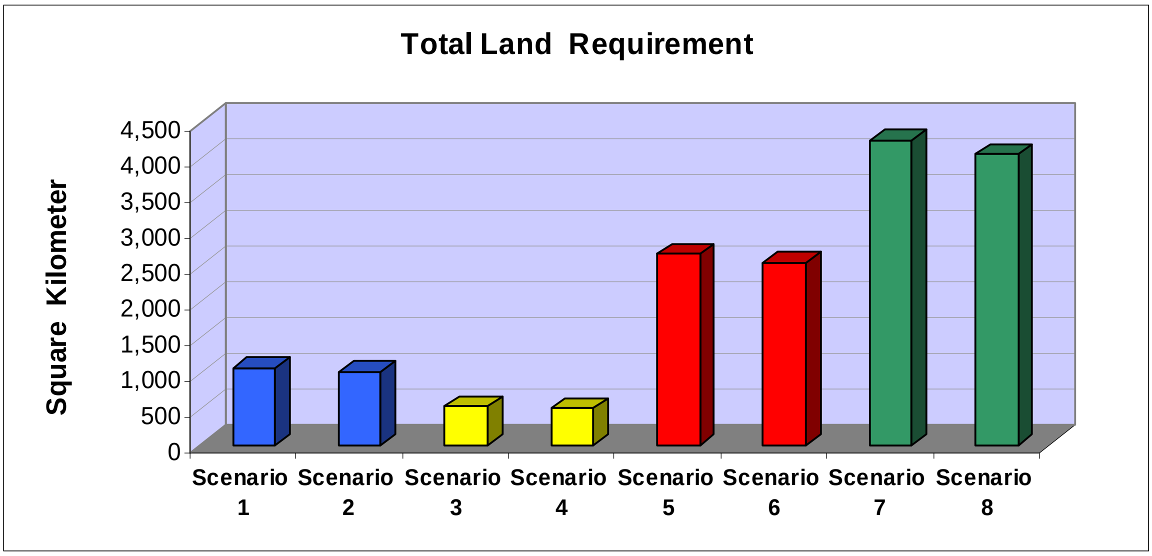


**Figure 12: Estimated total land requirement for the developed scenarios**

Figure 12 is actually based on typical land intakes which do not usually take into account any additional land that could be required for backup production. Moreover, the above estimates overlook the facts that many PV panels could have zero land usage as they could be mounted on roofs or as cladding to buildings. In addition, owing to the fact that part of the land area can be used for other purposes, e.g. agriculture, one could argue that the actual area devoted to wind-power generation (i.e. in the Red and Green Scenarios) is somewhat overestimated.

Finally, the figure below illustrates potential annual lifecycle savings that might be achievable in each of the developed renewable energy scenarios. These savings are essentially relative to a baseline/reference scenario that does not utilise any renewable energy technology.

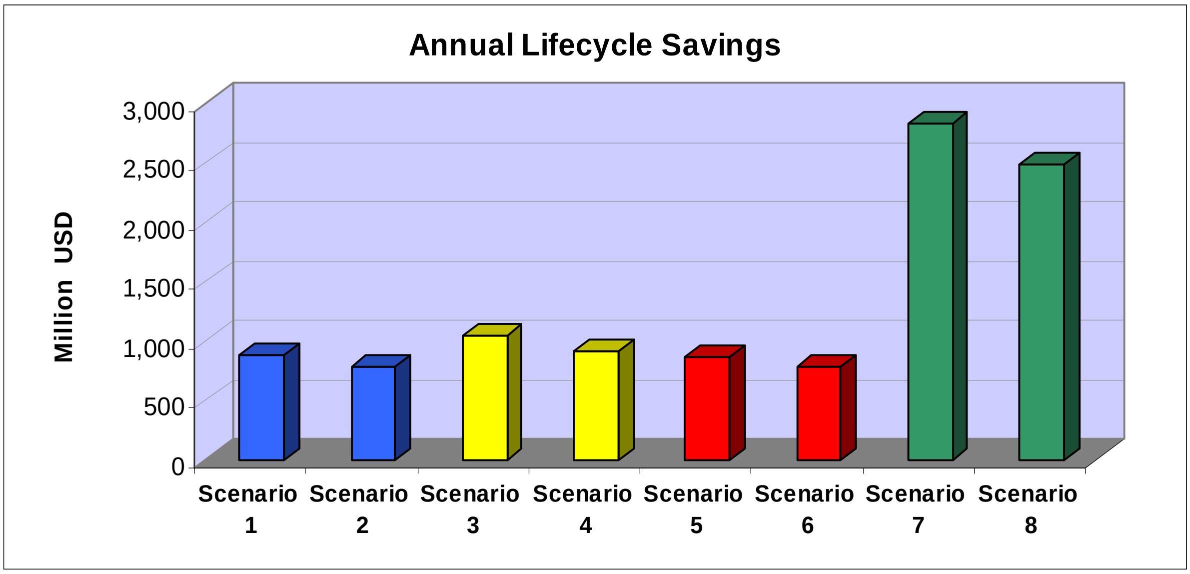


**Figure 13: Estimated annual lifecycle savings for the developed scenarios**

Such levelised lifecycle costs are not intended to provide a definite guide to actual electricity-generation investment decisions. Instead, their role should be limited to providing 'first order assessment'. For instance, an absolutely critical component of any levelised cost calculation is the discount rate, which - theoretically speaking - should be relatively high for capital-intensive and risky projects. Nevertheless, decades of debate over an acceptable value of discount rate for power plants have not yet produced a conclusive answer (UK Energy Research Centre, 2006).

## 9. Concluding Remarks

Many of the oil-rich Middle Eastern nations have benefited enormously from the recent surge in oil prices. This ample income has provided the Kingdom of Saudi Arabia, as a major oil-producer, with options that would have been unthinkable a few years ago. Among the challenges facing such oil-dependent economies, however, is how such an apparent wealth can be put to best use on the path to sustainable development. Demonstrably, almost all energy scenarios for attaining sustainability around the world take for granted a sizeable increase in the share of primary energy from renewable sources (e.g. Goldemberg, 2000; Hennicke, 2005; IPCC, 2001;

Shell International, 2001; Virdis, 2003). With the recent energy and environmental concerns, there is an apparent global enthusiasm for renewable energy options. Saudi Arabia, despite being a key oil producer should not be seen as an exception in this regard. It is believed that 'now' is the appropriate time to invest in developing capabilities in the field of renewable energy in order to secure the country's future for a sustainable economy and to address its rapidly-growing energy needs. The drive towards renewable energy in Saudi Arabia should not regarded as being a luxury but rather a must, as a sign of good governance, concern for the environment and prudence in oil-production policy.

Such a transition towards sustainable energy systems would essentially involve 'innovation' leading to more sustainable technological and institutional processes. Given that limited studies of sustainable innovation have actually drawn upon the theoretical concepts that have recently been developed within the realm of innovation studies, attempts to examine proceses through which such sustainable innovation take place would be useful, on both theoretical and policy-making fronts. More specifically, adopting an innovation system perspective seems as an attractive analytical framework, as it accomplishes a transition of the rationale for policy intervention from the typically limited approach of 'market failures' to a more appropriate 'systemic failures' approach. It is therefore recommended that further research be conducted in order to further examine, in the light of innovation system thinking, the prospects of renewable energy innovation in oil-rich nations such as Saudi Arabia. After all, the developed scenarios show that such an endeavour would not only be beneficial to Saudi strategic interests but also to the world as a whole. It is hoped that these scenarios will spur constructive debates on this crucial subject, and hence provide impetus for action in such major oil-producing nations. Until then, these scenarios - which were developed by informed individuals from diverse backgrounds - are subject to discussion, challenge, update and review as time passes.

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## Appendix A: Study Contributors

The author would like to express his special gratitude to the following individuals (listed in alphabetical order) for their invaluable contribution to the completion of this Delphi study:

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Prof. Mohammed Shwehdi
Dr. Viktor Schlosser
Dr. Nikolaus Supersberger
Dr. David Von Hippel
Dr. Ahmed Zoba

## Appendix B: Quantifying the Scenarios

It has been suggested that quantification, which is more appropriate for normative scenarios, risks shifting the emphasis of discussion to specific figures as opposed to consideration of the speculative nature of this explorative exercise. On the other hand, making only qualitative scenarios - without any calculations - would be a nice exercise, but it would not convince decision-makers nor will it spur practical debate on the subject. So, in the light of the mainstream view among the participating experts, it was decided to incorporate some quantification to the developed renewable energy scenarios for Saudi Arabia. Some intellectuals are evidently in favour of an engineering-based approach that utilises some sophisticated computer software packages, e.g. MARKAL software. Such computerised 'black box' macro-economic models, which are regarded by some as being 'rigorous', aim to pick up interdependencies that we know exist between supply and demand, adoption of competing technologies etc. by adopting a wide range of assumptions that are quite often hard - if not impossible - to test. On the other hand, many energy economists believe that all assumptions regarding the relationship between energy prices and the development of consumption are absurd. For instance, from what can be seen from our experience of recent years, one of the reputable experts has expressed his extreme suspicion of all economic/econometric models, and argued that almost all elasticity calculations are misleading. Since costs can come spiralling down owing to unexpected (and perhaps disruptive) innovation in some related or perhaps unrelated field, it might be pointless to quantify in detail the costs of different energy technologies for the year 2020, let alone 2050. The best way forward thus appeared to make some assumptions and try to work out some quantitative values to add some realism to the scenarios so that the decision-makers would be able somehow to quantify the effect of their decisions today on the next forty-two years. After all, numbers are both seductive and persuasive for politicians, and quite often appeal more and triumph over researchers' attempts to provide rich description (Easterby-Smith et al., 2001). It is also hoped that such simplified quantification would provide some useful additional policy information.

For each scenario, therefore, an end-point was set (i.e. the previously-assumed renewables targets, or a certain level of renewables penetration) and then the Delphi team worked backwards (in a backcasting style) to suggest how it could be realised. Table 4 illustrates the renewables target and the equivalent target contribution to the installed capacity by 2050.

**Table 4: Assumed renewables' ultimate contribution to Saudi power capacity by 2050**

| | Perception of Renewables | Total Installed Capacity in 2050 (GW) | Renewables Target for the year 2050 (%) | Renewables' Contribution to Installed Capacity by 2050 (GW) |
|---|---|---|---|---|
| **Blue, Yellow & Red Scenarios** | Positive | 122.59 | 15 | 18.39 |
| | Negative | 175.14 | 10 | 17.51 |
| **Green Scenarios** | Positive | 122.59 | 45 | 55.17 |
| | Negative | 175.14 | 30 | 52.54 |

Whilst the renewables' contribution in scenarios with positive perceptions has turned out to be slightly higher than in the case of negative perceptions, it should be noted that the former scenarios entail the application of financial incentives that would essentially boost the cost-competitiveness of renewables. Moreover, since the Yellow and Green scenarios – unlike the Blue and Red ones – envisage stringent concern and action for environmental protection, it is reasonable to assume the existence of greenhouse gas (GHG) emission-reduction credits which would further enhance the financial viability of renewables.

Assuming a typical lifetime for power plants of twenty-five years, and that the first plant is to be built and connected by 2010, whilst taking into account the previously-assumed power capacity installations and renewable targets, Figure 14 demonstrates a suggested plan for renewables additions for all scenarios. In essence, it is assumed that nine 'chunks' of renewable power will be required in each scenario every five years until 2050. These are assumed to be of equal magnitude for the sake of mathematical convenience, although one may presume that they start off small and then become larger by the end of the projection period.

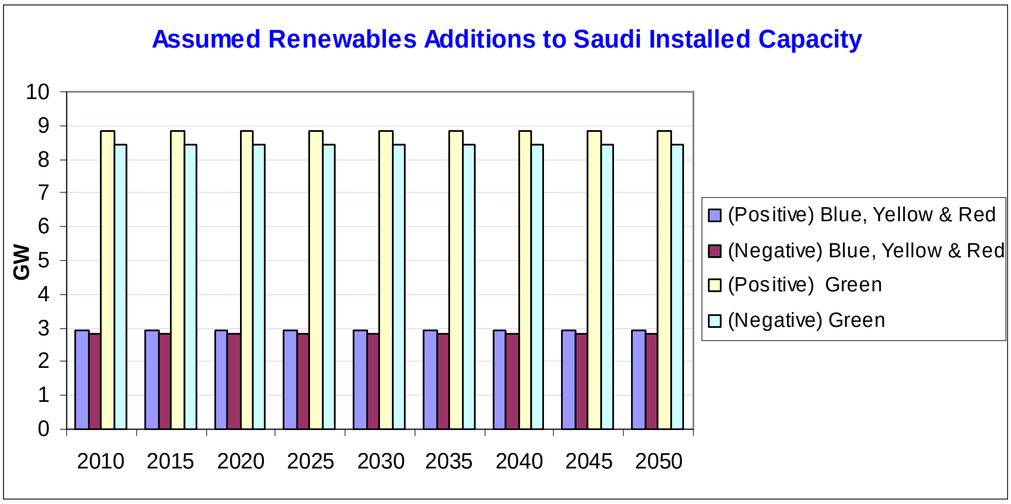


**Figure 14: Assumed renewables additions needed through to the year 2050**

According to IEA (2005) and to a few informed research participants, the vast majority of Saudi electric power (over 90%) is currently being generated by open-cycle gas turbines or steam boilers. The share of natural gas for electricity production in 2003 was estimated at 46% and is set to grow over the coming years. For the purpose of this study, therefore, the options of renewable energy technologies will be compared with what currently prevails (i.e. simple-cycle gas turbines that use natural gas as fuel). The possibility of using more efficient combined-cycle power plants in the future has already been accounted for in the assumed 30% reduction of installed capacity in the case of scenarios with positive perception of renewables (see Section 6.2). Whilst fuel price is a key component in the economics of such power plants, future prices clearly represent one of the largest areas of uncertainty. Table 5, based on data provided by the – seemingly somewhat neutral yet reputable – Japanese Central Research Institute of the Electric Power Industry (CRIEPI), anticipates international prices of natural gas until the year 2050. Whilst the Saudi Government might provide a fuel subsidy to the Saudi Electricity Company (or perhaps to any developer from the private sector), such subsidies should be ignored because this natural gas resource could have been saved for other purposes such as export and revenue-making purposes. Analysis will therefore take into account the cost of fuel to Saudi Arabia, which is usually the price that the country could get for that fuel on the international market.

**Table 5: Assumed natural gas price through to the year 2050**

| Year | Assumed Natural Gas Price (USD/$m^3$) |
|---|---|
| 2010 | 0.21 |
| 2015 | 0.24 |
| 2020 | 0.27 |
| 2025 | 0.30 |
| 2030 | 0.32 |
| 2035 | 0.37 |
| 2040 | 0.43 |
| 2045 | 0.54 |
| 2050 | 0.64 |

It should be noted here that the renewables in question are characterised by high capital cost and zero fuel cost, unlike conventional technologies in which fuel costs are high and initial investment is much lower than in the case of renewables. A lifecycle approach to power systems' economics is therefore required. Although several forecasts for future investment costs for power plants are available in the literature, a direct comparison is - at best - debatable and - at worst - misleading. Such estimates are typically based on a learning curve approach, i.e. an anticipation of future cost reductions based on past history and cumulative technology production over time. Figure 15 presents a rough estimate for the future capital costs for the power technologies considered in our scenarios (whether Saudi Arabia is relying on foreign or indigenously-developed power technologies). These estimates were produced; initially with the help of a few informed Delphi experts, and were later approved by the vast majority of the Delphi team. Such estimates were produced after studying experiences curves provided by IEA (2000), whilst bearing in mind several international estimates of investment assumptions for power technologies published by DLR (2006), Greenpeace and European Renewable Energy Council (2007), IEA (2003,2006), NEA and IEA (2005) and the US DOE (1997).

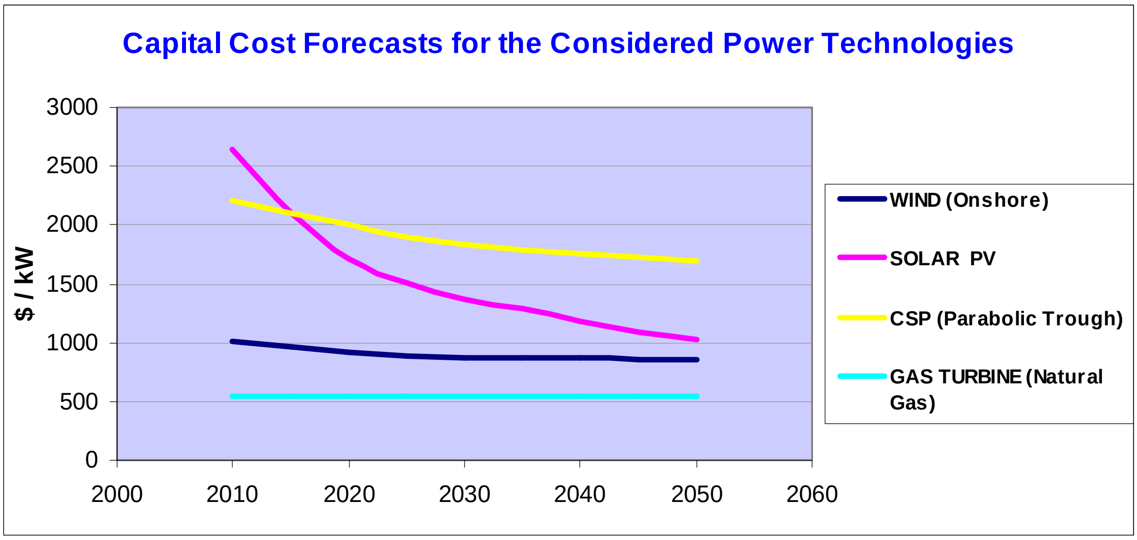


**Figure 15: Assumed capital costs for the considered power technologies**

For the purpose of producing preliminary lifecycle cost estimates, *RETScreen International Clean Energy Project Analysis Software* seemed to be an attractive and feasible tool to use. RETScreen Software provides an evaluation of lifecycle costs, financial viability and risk analysis for various types of energy technologies in order to determine whether or not the balance of costs and savings over the life of a power-plant project (i.e. cash flows) makes for a financially attractive proposition.[2] Whilst RETScreen Software does not account for 'external

[2] The detailed calculations and various mathematical equations used by the RETScreen Software are documented at: http://www.retscreen.net/ang/t_training.php

costs' to society and the environment owing to the burning of fossil-fuels, it calculates any greenhouse emission reductions that might result from the use of clean-energy technologies. This software is provided by Natural Resources Canada (NRCan) and has been developed with the contribution of several experts from government, industry and academia. Integrated within this software are databases for product, cost and climatic conditions (i.e. meteorological data sets from both ground and NASA satellite databases). Thus, based on the previously highlighted cost forecasts for capital and fuel and through the use of climatic data sets for Saudi Arabia, nine RETScreen models have been constructed for each of the eight scenarios in order to model the pre-planned nine renewables additions to the Saudi installed power capacity through to 2050.

**RETScreen Model Input Data**

Below are the adopted input data for the seventy-two RETScreen models. These were guided by an intensive literature survey as well as by an informed contribution from several Delphi experts.

- Power Plant lifetime 25 years
- Discount rate 8%
- Inflation rate 2.5%
- Debt ratio 50%
- Debt interest rate 7.7%
- Debt term 15 years
- Depreciation rate 30%
- Depreciation tax basis 95%
- Effective income tax rate 35%

- For all power plants, the transmission and distribution losses are currently assumed to be 20%. These are gradually to decrease to 10% by 2050.

- For wind turbines, the assumed array (wake) losses are 5%; airfoil soiling losses are 2%; downtime losses are 5%; and miscellaneous losses are 2%.

- The assumed Higher Heating Value of Natural Gas is 38,000 $kJ/m^3$.

- The annual Operation & Maintenance (O&M) costs for renewable power plants were assumed as a percentage of the initial capital cost of the system. Annual O&M for solar PV, wind and CSP are assumed to be 1%, 1.5% and 2.5% of the capital costs respectively. The assumed annual O&M costs for (natural gas-fuelled) gas turbines are fixed at 25 USD/kW.

- As previously highlighted, for the scenarios with high action on environmental protection (i.e. Solar and Green Scenarios), it is possible to obtain GHG reduction income – probably from outside Saudi Arabia – when clean energy technologies are used. The assumed GHG reduction credit rate is 5 USD/$tCO^2$ with an annual escalation rate of 2% and a fixed annual credit transaction fee of 2%.

- As previously highlighted for scenarios with positive perceptions of renewables, there will be a range of financial incentives as well as a gradual removal of current heavy subsidisation on electricity generated using fossil-fuels that could enhance the cost-effectiveness of clean-energy technologies. Whilst many scholars (e.g. Haas et al., 2001) argue that incentive mechanisms should focus on incentives per kWh generated as opposed to rebates on investment in generating capacity, such incentive mechanisms could only be accounted for in the RETScreen model in an input cell named 'incentives and grants'. This monetary value, which in effect is treated by the software as non-refundable income paid to reduce the initial cost of the power-plant, is assumed to be 20% of the capital cost of the renewable power plant. It is further assumed that this value would gradually increase by 0.5% per annum to make up for the pre-assumed gradual lifting of current subsidisation on fossil fuel-based electrical generation. Apparently, if incentives were provided by the government to build renewable generation, they would enhance the financial attractiveness of renewables for power investors/developers (particularly from the private sector and/or foreign investors), though they would not – under most circumstances – reduce the cost of renewable power to Saudi Arabia as a whole because any subsidy benefits would be cancelled out by the subsidy cost paid by the government. Government incentives for renewable energy investments may in some cases have other economic rationales – stimulating the growth of local renewable power-manufacturing industries and hence creating job opportunities as the country continues to face increasing unemployment rates, or saving oil and gas for future exports – but may have other motivations, including environmental, social and/or political rationales, that are of equal or perhaps greater importance.

- As previously highlighted, there will be an extensive application of energy saving-measures in the scenarios with positive perceptions of renewables. The pre-assumed 30% cumulative reduction of required power capacity by the year 2050 will (at least partly) be achieved by the purchase of better electric motors, efficient lights, appliances, controls, etc. In some cases, these improvements may be at no extra cost relative to the scenarios with negative perceptions of renewables (i.e. non-energy-efficiency-scenarios), but in most cases there will be an additional cost involved. This additional cost item is usually referred to as 'cost of saved energy', and was estimated by the Delphi participants to be around $20/MWh, i.e. an average over a range of different sectors, end-uses and energy improvement measures. Thus, if energy consumption is reduced by X MWh in a given year, that reduction in consumption may cost $20*X in that year. It should be noted however that the $20/MWh is essentially a 'levelised' value, i.e. it is what one pays for each MWh saved over the lifetime of the project. Such an additional cost will definitely be more than offset by the savings in fuel, O&M and capital costs for the power-plants whose construction or use is avoided.

- For the purpose of this exercise, the technology model selected for the Open Cycle Gas Turbine is **GE MS6001B** (42.1 MW); and for the Wind Turbine it is **Vestas V90** (3 MW). Solar PV and Solar Thermal CSP were based on the technologies of **BP Solar**.

Finally, it should be noted that integrated within the RETScreen Software are databases that include product specifications for a number of the power technologies of various manufacturers. These specifications are essentially today's state-of-the-art and do not account for potential technological improvements in the future. Whilst a sensible energy analyst should not believe that there are going to be any miracle solutions pulled out of the hat, many long-term energy scenarios tend to assume a gradually increasing capacity factor for future power plants. The capacity factor of a power plant can be defined as the ratio of actual power over a period of time and its output if it had operated at full nameplate capacity the entire time (Ellicott et al., 1998). In the case of solar PV, whilst the conversion efficiencies of PV cells are around 10-15% at present, the highest (theoretical) efficiency obtainable from silicon-based PV cells is approximately 29%, an upper limit that might possibly be approached by the year 2050. In addition, one of the ways to significantly improve the capacity factor is to have PV arrays that could track the sun. It is thus reasonable to assume that CSP plants have a slightly higher capacity factor than PV as they are more likely to use tracking collectors. Since the sun is above the horizon no more than 50% of the time in a year, however, the capacity factor of solar power-plants is usually less than 50%. The only way that today's solar technologies may appear to have a capacity factor greater than 50% is either if they were in hybrid configurations or through the use of energy storage for night-time generation. If the latter options are implemented, modern installations could have an overall capacity factor of 70-90%. In essence, increasing the capacity factor of power-plants should lead a better lifecycle economics because a high capacity factor translates to a higher MWh produced from a given installed MW. It should, however, be noted that the technology that was voted among the three preferred renewable energy options for Saudi Arabia is the simple CSP plants without storage. On the other hand, future wind turbines are likely to become larger and perhaps a bit more efficient – on average – over time, which may improve the capacity factor somewhat. The capacity factor of wind farms is, however, more influenced by where the turbines are located. Since Saudi locations with the best wind resources are likely to be used first, the capacity factor of future wind farms may tend to decrease. Countervailing that trend perhaps will be improvements in technology that will allow the use of wind turbines at lower wind speeds (e.g. see Horizon Wind Energy, 2004). Based on an intensive literature review that was supplemented by the informed views of participating experts, Table 6 summarises the assumed capacity factors for the power plants under consideration:

**Table 6: Assumed capacity factors for the power plants under consideration**

| | **2010** | **2050** |
|---|---|---|
| Capacity Factor for **Wind Turbines** | 28% | 35% |
| Capacity Factor for **Solar PV** | 30% | 40% |
| Capacity Factor for **CSP** | 36% | 45% |
| Capacity Factor for **Gas Turbines** | 75% | 80% |

Thus, when all the above are taken into account, total lifecycle ‘savings’ for each renewables addition =

Total fuel cost savings (i.e. cost of fuel for a reference scenario of gas turbine-based plants only)

+ Total O&M savings vis-à-vis the reference scenario (i.e gas turbines with zero renewables)

– Total levelised debt payments to pay off the capital cost (i.e. difference between capital cost of new renewables plants and that of gas turbine installations in the reference scenario)

+ Any revenue resulting from GHG reductions (in the case of the Yellow and Green scenarios)

+ Any financial incentives to promote renewables (in scenarios with positive perceptions)

– Cost of saved energy (in scenarios with positive perceptions)

The above calculations were conducted for each of the proposed nine renewables additions within each of the developed eight energy scenarios. The calculated lifecycle savings for the nine renewables capacity additions were then averaged in order to obtain averaged lifecycle savings for each scenario (see Figure 13).

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