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Cost Effectiveness Analysis for Renewable Energy Sources Integration in the Island of Lemnos, Greece

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Abstract: The development of more efficient and least cost energy management interventions is of great importance for isolated energy systems. Islands are typical examples of isolated regions, often highly dependent on imported fossil fuels but with a significant and often unexploited Renewable Energy (RE) potential. This paper presents a least cost planning approach towards the integration of Renewable Energy Sources (RES) in such systems, which is applied to the island of Lemnos, Greece. The approach involves the application of Cost-Effectiveness Analysis (CEA) and Incremental Cost Analysis (ICA) for screening possible alternatives and determining the most economically efficient and effective plan for their implementation. The objective of the application of the proposed approach in the specific case study is to meet through the use of RE technologies all the additional electricity and thermal energy demand, compared to 2007. Various supply side options are evaluated, and an implementation plan is derived. The results indicate that the excess of both electricity and thermal energy demand can be met in the near future without any significant changes in existing infrastructure, while other options should be considered for a more extended time horizon.

Keywords: Renewable Energy Sources (RES); Cost Effectiveness Analysis (CEA); Isolated Energy Systems; Incremental Cost Analysis (ICA); Implementation Plan.

1. INTRODUCTION

Isolated energy systems are characterized by geographical discontinuity, which causes difficulties of interconnection to the main electricity grid and increases the cost of transporting fuel. Furthermore, when there is limited potential for indigenous fossil fuel production, all the above, along with the increase in energy demand, can create problems that affect sustainable energy management.

Islands are typical examples of isolated regions, often highly dependent on imported fossil fuels, but also often having significant potential of Renewable Energy Sources [Rei et al., 2002]. According to the European Island Agenda [1997], the continuing exploitation of non-renewable energy sources is a provisional solution, inadequate to address energy problems in the long term. Thus, the higher penetration of RES is the only choice that could contribute towards energy autonomy, more stable energy prices and sustainable economic growth in these regions.

This paper outlines a methodological approach for planning efficient and least-cost integration of RES in isolated energy systems. The approach involves the application of

Cost-Effectiveness Analysis (CEA) and Incremental Cost Analysis (ICA) for screening possible alternatives and determining the most economically efficient and effective plan for their implementation, taking into account projections of future energy demand. The benefits of the proposed approach, as compared to optimization techniques, comprise the ease of implementation and the ability to define the optimal interventions within a complex range of alternatives through a transparent process. It should be noted that CEA and ICA do not identify a unique or "optimal" solution, but can lead to better-informed choices among alternative solutions, providing a basis for comparison of the relevant changes in costs and outputs on which such decisions should be made [Yao, 1992]. In such analyses, costs are typically calculated as the direct financial or economic costs of implementing a proposed measure, with effectiveness being defined in terms of some physical measure of environmental outcome [RPA, 2004]. Thus, the two methods provide results that can easily be interpreted and evaluated by policy makers and/or a wider audience.

Furthermore, and with regard to the specific goals of energy planning, the selection of CEA over traditional cost-benefit analysis allows addressing the different benefits of RE integration swiftly and objectively. Through the choice of appropriate indicators, local benefits associated with improved environmental quality, economic growth, job creation, increased control of energy production and energy supply security can easily be taken into account, while at the same time avoiding the time-consuming and often biased procedure of assigning monetary values to benefits.

Following this brief introduction, Section 2 presents the proposed methodology, and in Section 3 the methodology is applied to the island of Lemnos in Greece and the results are discussed. Finally, Section 4 summarizes the conclusions and makes suggestions for further research.

2. METHODOLOGY

Cost-effectiveness analysis (CEA) is a form of economic analysis that compares the relative expenditure (cost) and output (effectiveness) of two or more courses of action (options). The final result is a set of solutions (combinations of options) which can achieve the objectives set at the minimum cost. The identification of these solutions is performed through a relatively easy procedure, which consists of nine standard steps grouped in four tasks [Orth, 1994]. The 1st task focuses on the estimation of the cost and effectiveness of all available options, the examination of their compatibility and the formulation of the alternative solutions by combining these options. The measure of effectiveness is chosen to reflect the objective set as closely as possible. All cost and output estimates need to be measured over the same time period and in the same unit of measurement. That is, outputs and costs can be estimated either on an average annual basis or on a total output and cost basis [Robinson et al., 1995].

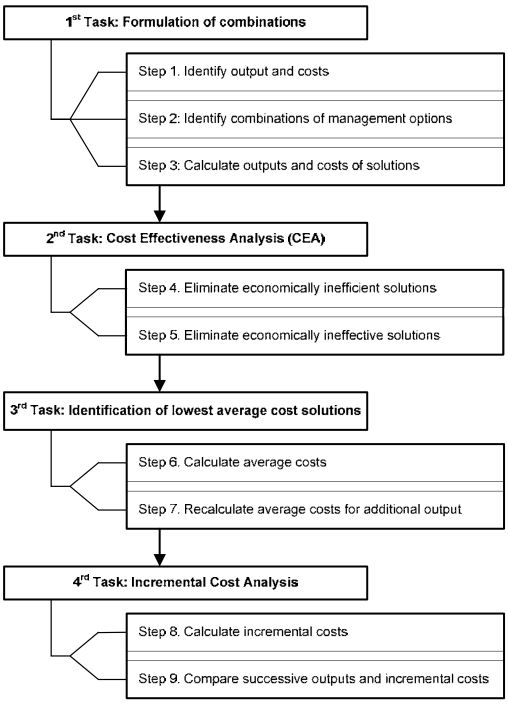

Figure 1. Cost-effectiveness analysis steps

The 2nd task performs the cost-effectiveness analysis, in order to eliminate inefficient or ineffective solutions. Inefficient are the solutions which, for the same amount of output, have greater cost than others, whereas ineffective those that for less output have the same or higher costs. The 3rd task calculates the average cost of the cost-effective solutions, in order to eliminate those that have lower total cost but are relatively inefficient in output. Although this task is optional, it can help to eliminate distortions in the ICA, which is performed in the 4^{th} task. The overall aim of ICA is to reveal changes in cost as levels of outputs increase, in order to determine whether the next level of the output is economically effective. Therefore, in this last task, successive solutions are compared against their incremental cost, in order to establish whether the next level of output is worth the additional monetary cost. The incremental cost (often mentioned also as marginal cost) is the change in cost that results from a decision, and is calculated by dividing the difference in cost between two successive solutions by their difference in output. The final step is the development of the incremental cost curve, a column chart that presents the incremental cost of the cost effective solutions. The incremental cost curve makes the relationship of cost and output for each alternative, as well as the variation in cost and output across alternatives, more visually apparent, in order to ascertain whether the next level of output is economically effective [Gerasidi et al., 2003].

According to Robinson et al. [1995], the following guidelines related to outputs, costs and the incremental curve can be used to assist in the decision making process:

(a) Curve Anomalies. Abrupt changes in the incremental cost curve, such as a breakpoint, a spike or a peak, which may indicate a sharp incremental cost increase, are potential decision points.

(b) Output Target. If a study has established a specific resource target to be met, then a decision rule could be developed to partially or fully meet that target.

(c) Output Thresholds. In some cases, it may be necessary to initially produce a minimum (or maximum) base amount of output and any lesser (or greater) amount would not contribute to the achievement of the objectives set. If such thresholds exist, they can be utilized to identify the range of acceptable solutions.

(d) Cost Affordability. If implementation funds are a constraint, then decision makers can review the curves that will help them identify the best investment for the funds available.

3. CASE STUDY

In this paper, the methodology described above is applied to the island of Lemnos, Greece. The island is located in the N.E. Aegean Sea (Figure 2), has a total land surface of 478 km^2 and a population of 18,104 (Census of 2001). The island is not connected to the mainland electricity grid. Its power system consists of a thermal power plant (5 fuel oil-fired engines with a total installed capacity of 19,640 kW and a diesel-fired engine of 1,500 kW) and a wind park of total installed capacity 1,140 kW. All the non-renewable primary energy resources are imported from the mainland. Hence, the use of RES in the island would be an important step towards ensuring energy autonomy and security.

Figure 2. Location of Lemnos Island

Previous works have estimated the electricity and thermal energy demand for 2007 at 53,530 and 67,170 MWh respectively [Angelis-Dimakis, 2005]. An assessment of the RE potential of the area has pointed towards the possibility for substantial integration of RE into the island's energy system. In more detail, the meteorological data of the island indicate fairly strong winds throughout the year (mean annual wind speed ~5m/s) and long sunny periods (mean daily solar radiation on horizontal surface ~4.8 kWh/m^2d). Geothermal resources also exist in Lemnos, with temperatures of hot waters reaching 50^{o}C.

The main agricultural product of the island is wheat, which leaves a great amount of biomass residues (almost 25,000 tons per year) that could be utilized for heating purposes [Trogadas, 2005]. The RE technologies chosen are wind turbines, photovoltaics, solar water heating systems, ground source heat pumps and biomass heating systems.

The overall goal of the case study is to define an implementation plan that could satisfy all the additional, as compared to 2007, electricity and thermal energy demand through the use of RE technologies. Three different scenarios have been formulated for the energy demand projection. The Business As Usual (BAU) scenario was based on historical data, assuming different energy demand growth rates for each sector according to the Public Power Corporation's forecast for electricity demand [Karalis et al., 2000]. The High Energy Demand (HED) scenario assumes the establishment of a University Department on Lemnos, an option which is currently under discussion, and a subsequent increase in population and energy demand. Finally, the Low Energy Demand (LED) scenario assumes that population increases at declining rates and that lower growth rates will be observed over the coming years. All the above scenarios have been formulated and analysed through the Long range Energy Alternatives Planning (LEAP) software, a package developed at the Stockholm Environment Institute for analysing energy balances and forecasting future energy demands.

Table 1. Alternative energy management options examined

Actions	Alternative Options	Energy Produced (MWh)	Annual Cost (€)	Code
Electricity Demand				
Wind Turbines	1×850 kW	2460	134280	A1
	3×850 kW	7230	290181	A2
	5×850 kW	11800	443902	A3
Photovoltaics (PV)	Myrina Hospital	47	23559	E1
	Myrina Town Hall	31	15689	E2
	100 Houses	360	207800	E3
	250 Houses	900	519500	E4
	500 Houses	1800	1039000	E5
Thermal Energy Demand				
Biomass Heaters (BH)	Moudros High School	149	7803	B1
	Moudros Lycee	62	6576	B2
	Moudros TEE	124	7241	B3
Geothermal Heat Pumps (GHP)	"Myrina Beach" Hotel	2230	68343	C1
	"Lemnos Village" Hotel	740	22964	C2
Solar Water Heaters (SWH)	100 Houses	240	12500	D1
	250 Houses	600	31250	D2
	500 Houses	1200	62500	D3
	1000 Houses	2400	125000	D4

Feasible and acceptable options were selected and evaluated (Table 1) after site investigation and consultation with local stakeholders. Wind turbines can be installed in the existing wind park, taking into account the limitations of the autonomous network concerning the total installed capacity. For this purpose, a medium size wind turbine is selected and all alternative options have been formulated so that the total installed capacity does not exceed 40% of the island's peak load. The remaining RE technologies can be installed in public buildings and households of the island's two largest towns Myrina, the capital, and Moudros. Moudros, located in a rural area, has been chosen as the suitable site for biomass exploitation technologies, in order to minimize the corresponding transportation costs. On the other hand, Myrina, where all the public services and hotels are located, has been chosen for the installation of solar and geothermal technologies. The number of additional solar water heaters and photovoltaics was calculated taking into account (a) the number of available houses (~5000) and (b) the share of houses that already have a solar water heater installed (around 40%), further assuming that solar technologies can be installed in at least 50% of the remaining houses. As solar water heaters are a very popular technology in Greece, it was also assumed that they would have a larger penetration than PVs, accounting for 2/3 of the units installed.

Cost estimates presented in Table 1 correspond to the total annual cost for the implementation of each option, which comprises: (a) the amortization of the initial investment cost and (b) the annual operation and maintenance costs. Investment costs include design, transportation and installation costs, where applicable, and equipment purchase costs.

In order to account for all potential benefits from the exploitation of RES on the island's energy balance, the effectiveness of each option was expressed in terms of the annual renewable energy delivered by each option. The annual energy production for the renewable energy technologies was calculated using RETScreen, a standardized and integrated renewable energy project analysis software developed by the Natural Resources Canada's (NRCan) CANMET Energy Technology Centre - Varennes (CETC-Varennes).

As the target of the analysis is to satisfy both electricity and thermal energy demand, two separate analyses were developed, the Electricity Production Analysis (EPA) and the Thermal Energy Production Analysis (TEPA), using software developed at the Environmental & Energy Management Research Unit (EEMRU), an educational and research unit in the School of Chemical Engineering at the National Technical University of Athens (NTUA).

Figure 3 and Table 2 present the results of the Cost-Effectiveness Analysis. Out of the total of 65 (EPA) and 161 (TEPA) possible and acceptable solutions (combinations of options) that emerged as a result of Task 1, four and six solutions respectively have been identified as economically efficient and effective (Task 2). It should be noted that each point of Figures 3a and 3b represents the cost and effectiveness of the respective solution. The curve joining all the cost effective solutions is referred to as the Cost Effectiveness Frontier (CEF). All the remaining solutions located above and to the left of the CEF are economically ineffective or inefficient.

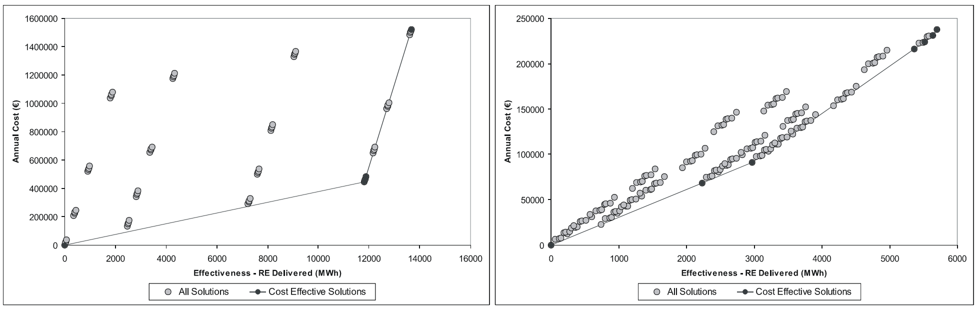

Figure 3. Estimated outputs and costs of all solutions and cost effective solutions for (a) electricity production analysis and (b) thermal energy production analysis.

Figure 4 presents the results of Tasks 3 and 4 of the ICA. Each column within the graph represents the incremental cost and incremental output associated with the respective solution. The difference in incremental cost between two successive columns indicates the per unit additional cost that should be paid in order to reach the next level of output. Results from the ICA show that in the set of cost effective solutions for meeting electricity demand there is a sharp incremental cost increase from the first (5×850 kW Wind Turbines) to the second level of output, which involves the introduction of photovoltaics in public buildings. This implies that additional demand-driven management options need to be examined before further capacity expansion is decided. On the contrary, in TEPA transition from one level of output to another is smoother, with the sharp increase in incremental cost being observed only for the production of the last 124 MWh.

Table 2. Cost effective solutions

Electricity Demand		Thermal Energy Demand	
Solution	Description	Solution	Description
EL1	5×850 kW Wind Turbines (A3)	TH1	GHP in “Myrina Beach” Hotel (C1)
EL2	EL1 + PV in Myrina Hospital (E1)	TH2	TH1+GHP in “Lemnos Village” Hotel (C2)
EL3	EL2 +PV in Myrina Town Hall (E2)	TH3	TH2 + SWH in 1000 Houses(D4)
EL4	EL3 + PV in 500 Houses (E5)	TH4	TH3 + BH in Moudros High School (B1)
		TH5	TH4 + BH in Moudros Lycee (B2)
		TH6	TH5 + BH in Moudros TEE (B3)

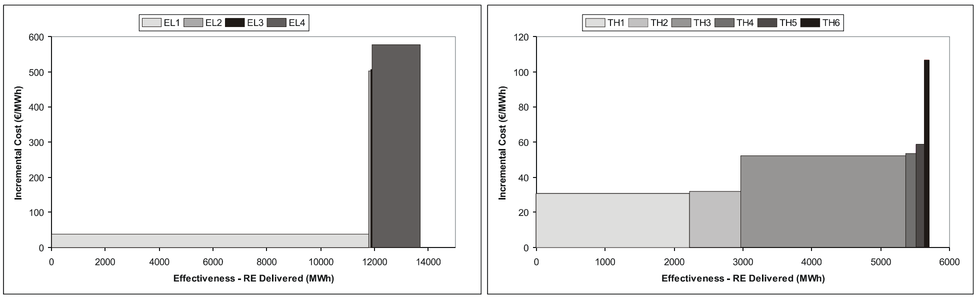

Figure 4. Incremental cost analysis for the cost effective solutions

While formulating an implementation plan, emphasis is placed on reaching the output targets set, i.e. meeting through RES all electricity and thermal needs exceeding the 2007 demand level. The ability of meeting the extra demand is examined for each of the three scenarios and the results are presented in Figures 5, 6 and 7. The curve expresses the estimated energy demand, electrical or thermal, in figures (a) and (b) respectively. The columns for every year correspond to the total energy that can be supplied, i.e. the sum of demand that is met in the base year and the additional demand that can be met through the implementation of the chosen options. The gap between the curve and the columns represents the demand that is still unmet.

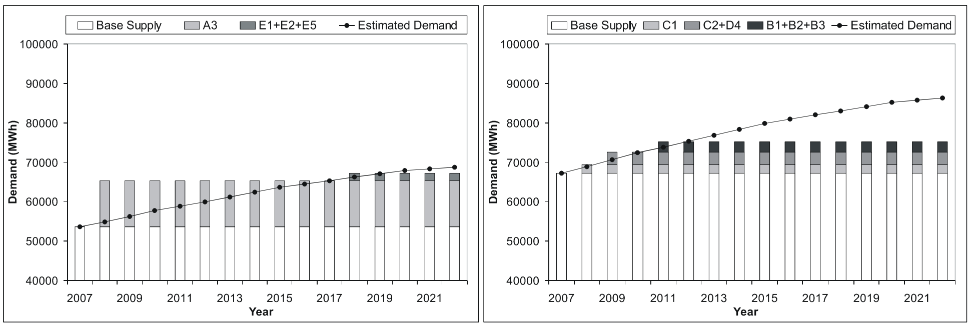

Figure 5. Formulation of the implementation plan for (a) electricity production analysis and (b) thermal energy production analysis. (BAU Scenario)

Results show that electricity demand can be met satisfactorily through RE technologies at least for the next decade, even under the most pessimistic forecasts. The total cost incurred is approximately 500,000€ for the BAU and LED scenarios, and increases up to three-fold in the HED scenario. On the contrary, the satisfaction of thermal energy demand is feasible only up to 2010 in the worst scenario (HED), or up to 2013, in the best scenario (LED). In a decade, the unmet thermal energy demand will be ranging from 5%, in the case of optimistic forecast (LED), to 16%, for the HED scenario. Meeting this demand would require (i) demand-side interventions (increasing efficiency in energy use), and (ii) measures aimed at inducing behavioural change towards lower energy consumption. A provisional plan for the implementation of the different options in each scenario is presented in Table 3. The interventions up to 2012 are of first priority. Given that the implementation of the remaining options corresponds to a sharp increase of incremental costs, their implementation should be re-assessed, taking into account the actual evolution of energy demand by 2012.

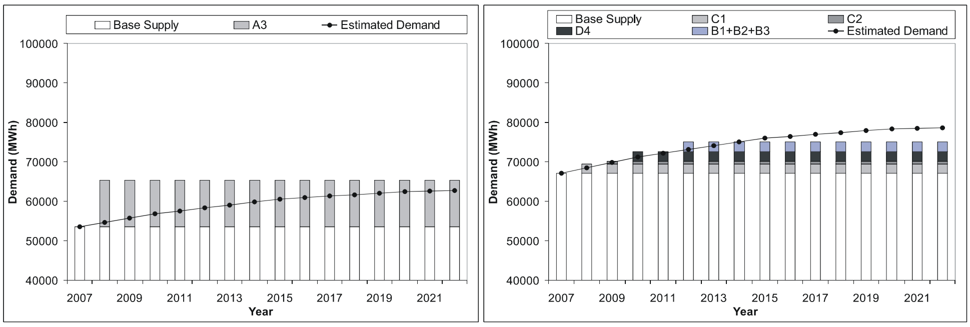

Figure 6. Formulation of the implementation plan (a) electricity production analysis and (b) thermal energy production analysis. (LED Scenario)

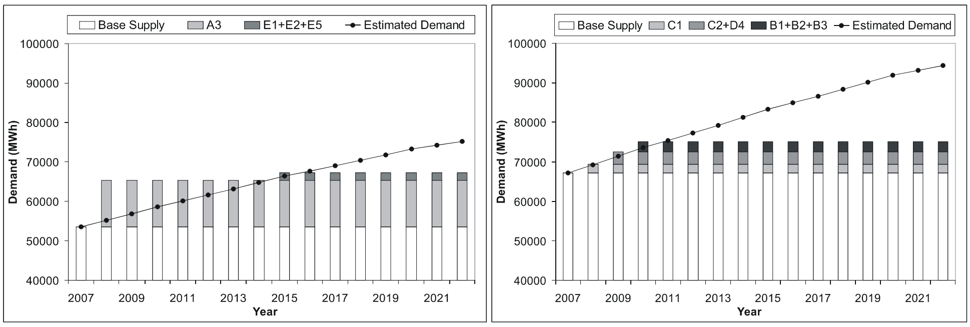

Figure 7. Formulation of the implementation plan for (a) electricity production analysis and (b) thermal energy production analysis. (HED Scenario)

Table 3. Implementation Plan for each scenario

Year	BAU	LED	HED
2008	5×850 kW Wind Turbines & GHP in "Myrina Beach" Hotel	5×850 kW Wind Turbines & GHP in "Myrina Beach" Hotel	5×850 kW Wind Turbines & GHP in "Myrina Beach" Hotel
2009	GHP in "Lemnos Village" Hotel & SWH in 1000 Houses	GHP in "Lemnos Village" Hotel	GHP in "Lemnos Village" Hotel & SWH in 1000 Houses
2010		SWH in 1000 Houses	BH in Moudros High School, in Moudros Lycee & in Moudros TEE
2011	BH in Moudros High School, in Moudros Lycee & in Moudros TEE		
2012		BH in Moudros High School, in Moudros Lycee & in Moudros TEE	
2015	PV in Myrina Hospital, in Myrina Town Hall & in 500 Houses		
2018			PV in Myrina Hospital, in Myrina Town Hall & in 500 Houses

4. CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

This paper introduces a methodological approach for planning efficient and least cost integration of RES in closed and isolated energy systems, based on cost effectiveness and incremental cost analysis. The approach is applied to the island of Lemnos, where results show that the additional, compared to 2007, electricity and thermal energy demand can be met in the near future, without significant changes in existing infrastructure. However, for a more extended time horizon, other options should be considered.

The proposed approach provides a consistent and easy-to-apply methodology for assessing energy management options according to their annual energy production and cost. As all selected options involve integration of Renewable Energy Sources, the annual energy production indicator does not only address the overall energy balance issue, but is also linked to wider environmental and socio-economic objectives. It should however be noted that the overall approach can easily be adapted to specifically address multiple objectives, through the selection of appropriate indicators representing economic, social or environmental criteria.

The environmental impact of the selected options has not been directly taken into account in this work; however environmental aspects, such as reduced emissions, protection of vulnerable ecosystems, etc., can be incorporated in the analysis to indicate trade-offs among the possible options. Individual decision makers can use these data to make planning decisions, depending on local development priorities and conditions.

Furthermore, an area of future research is to incorporate uncertainty in estimations of effectiveness and cost. According to Haimes [2004] uncertainty might stem from at least five different sources: (a) model topology, (b) model focus, (c) model parameters, (d) data used and (e) human subjectivity. In this regard, stochastic elements can be introduced to identify the impact of uncertainty in both the selection and the time-plan for the ranking of the different options.

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Implementation of a GEOdatabase to administrate global energy resources

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Abstract: The future development of our energy system is still unclear. This uncertainty is based on numerous aspects. In addition to the currently most relevant climate debate this will also be a question of available technologies as well as of available resources. Hence the global energy resources and their distribution will be one of the most influencing factors in the design of our future energy system. To model and administrate global energy potentials a geographical (GEO) database has been implemented. The intention to implement such a global GEO database is based on the fact that numerous aspects describing our energy system rely on spatial characteristics. Particularly renewable energy resources depend on numerous datasets, the most important ones are topography, land cover, climate, population distribution and precipitation. With respect to these datasets the theoretical and furthermore useable global potentials of renewable energy carriers were estimated, in this paper the computation of wind power is shown exemplarily. When modelling renewable energy potentials special attention has to be paid to the fact that renewable energy potentials are often not additive, what means that the land surface is only available once and therefore several potentials exclude the option to yield another potential on the same area. For the estimation of the highest possible energy potential on a certain area, a competition analysis regarding the utilization of the land surface was carried out.

Keywords: Energy resources, GIS, Global Database, modelling.

1. INTRODUCTION

Numerous statistics give numbers on energy potentials on country level (IAEA 2005, BP 2006, EIA 2005, WEC 2004) but only few studies reflect the real spatial and temporal distribution of - especially renewable - energy carriers. One work treating this issue quite fundamentally has been done by Hoogwijk [2004]. Nevertheless also in this work the chosen spatial resolution is quite rough (0.5°). Since primary geographic information like topography, land cover, climate are available in a quite high spatial resolution for the whole globe (up to 1km), an estimate on the related renewable energy potentials can be evolved in the same high spatial resolution. That issue is treated in the current paper and a global GEOdatabase including conventional and renewable energy potentials is developed.

The GEOdatabase not only includes the consideration of the global spatial distribution of single conventional and renewable energy resources but also the influence of their spatial distribution in the context of the complete energy system and the coupling with spatial energy demand structures.

2. BASIC FRAMEWORK

The intention of the GEOdatabase is to consider all relevant energy resources with their geographical distribution in one common database. As the input all relevant raw data like solar insolation, wind speed, precipitation, topography, land cover, etc. are used on a global scale. These datasets are included in the database, each describing one aspect of the energy