# Optimal design of the renewable energy map of Greece using Weighted Goal-Programming and Data Envelopment Analysis

Eleni Zografidou[1], Konstantinos Petridis[2], Garyfallos Arabatzis[1], Prasanta Kumar Dey[2,*]

[1]Department of Forestry and Management of the Environment and Natural Resources, Democritus University of Thrace, Pantazidou 193, 68200 Orestiada, Greece

[2]Aston Business School, Aston University, Aston Triangle, Birmingham B4 7ET, UK

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* corresponding author Tel: +44 121 204 4011, Fax:+44 121 204 5271, e-mail: p.k.dey@aston.ac.uk

## Abstract

Renewable energy forms have been widely used in the past decades highlighting a “green” shift in energy production. An actual reason behind this turn to renewable energy production is EU directives which set the Union’s targets for energy production from renewable sources, greenhouse gas emissions and increase in energy efficiency. All member countries are obligated to apply harmonized legislation and practices and restructure their energy production networks in order to meet EU targets. Towards the fulfillment of 20-20-20 EU targets, in Greece a specific strategy which promotes the construction of large scale Renewable Energy Source plants is promoted. In this paper, we present an optimal design of the Greek renewable energy production network applying a 0-1 Weighted Goal Programming model, considering, environmental and economic criteria. In the absence of a panel of experts Data Envelopment Analysis (DEA) approach is used in order to filter the best out of the possible network structures, seeking for the maximum technical efficiency. Super-Efficiency DEA model is also used in order to reduce the solutions and find the best out of all the possible. The results showed that in order to achieve maximum efficiency, the social and environmental criteria must be weighted more than the economic ones.

*Keywords*: Renewable energy, Goal Programming, Data Envelopment Analysis, Energy production

## 1. Introduction

The design of a country's energy map and the investment proposals for making it complete and responsive to national needs, are subjects that need interdisciplinary approach. This is because investing in energy incorporates not only energy production and consumption but it also has social, economic and environmental aspects. Investing in the energy sector and in energy plants in particular is not only financially evaluated; other criteria such as environmental pollution, gas emissions, social acceptance and the economic effects are considered important too. Sometimes making the trade off among them is also a point of conflict.

In European Union, both energy and environment are subjects of great importance and there are plenty of directives to promote the competitive, sustainable and secure energy but in a tight environmental framework policy that adapts Kyoto protocol in terms of greenhouse emissions' reduction. The EU Directive 2009/28/EC EU [1] '*Promotion of the use of energy from renewable sources'* subsequently repealing the EU Directive 2001/77/EC [2] and EU Directive 2009/29/EC [3], incorporates the basic principles for the use of renewable sources in the energy production, aiming to limit greenhouse gas emissions, like $CO_2$ and $NO_x$, and encourages the deployment of national energy plans including renewable energy sources. Furthermore, in this direction each European member state has a target of renewable energy production to gross final consumption ratio for 2020, which is included in the overall 20-20-20 Community's goals. Additionally, in the pursuit of the EU climate targets the greenhouse gas emissions should be reduced by 20% and an increase in energy efficiency by 20% should be achieved.

In Greece, due to the Greek Legislation (Law N. 4001/2011) every month an imprinting of the fundamentals of Renewable Energy Sources (RES) and of High Performance Stations which cogenerate Electricity and Heat is conducted. As it is stated in the recent reports so far for 2014, the total national installed capacity of renewable energy plants is 4.482MW and the total energy production of renewable energy plants is 682GWh. At the same time the 2014 goal for the total national installed capacity of renewable energy plants is 9.520MW and for 2020 is 13.950 MW (Renewable Energy Sources and High Performance Electricity and Heat Stations Report, 2014). The deviation from the goals is approximately 300%. At the same time the $CO_2$ levels from fossil fuel from 2012 to 2013 decreased approximately 10.2% (from 85.268 to 76.614 thousand tonnes) based on Eurostat reports of year 2014.

The Greek national energy plan for achieving 20% in renewable energy production to gross final consumption ratio, includes investments to renewable energy plans in the sector of electrical energy production, in household's heating and cooling and the use of biofuels in transportation. Furthermore, it is estimated that the overall investments needed in the energy sector are approximately to 22.2 billion euro for the ten-year period 2010-2020 from which 74,32% will be invested to Renewable Energy Sources. More specifically, the plan promotes the construction of large scale RES plants, such as wind farms, hydro plants and Concentrating Solar Power (CSP) plants, in conjunction to medium and small scale RES plants, including photovoltaic, small hydro, biogas, geothermal plants, biomass and co-generation and RES applications for electricity generation in the residential and tertiary sector buildings according to Ministry of Environment, Energy and Climate Change.

Nevertheless, recent studies give Greece a really low score of Climate Change Performance Index concluding that Greece has almost totally abandoned all climate policies under the effects of the economic crisis and Troika's economic control [4]. These facts point the interest to promote the national strategy of Renewable Energy Planning proposing radical and applicable policies considering energy, economic, environmental and social factors.

However, restructuring the energy production network of the country in order to meet EU targets, affects the country in a variety of ways including social, environmental and economic. This is the main reason why choices such as selecting among the different types of RES plants and selecting the place of their installation, should be made considering not only the financial effectiveness, the produced energy and the levels of GHG emissions, but also the social acceptance and the impacts on local and national economy in terms of unemployment and GDP. The data for unemployment and GDP for the Greek prefectures have been retrieved from Hellenic Statistical Authority (EL.STAT) for the fiscal year 2013.

Towards this direction, in the current work we present the optimal design of the Greek renewable energy production network applying a 0-1 weighted Goal Programming model. In our approach we take into consideration energy, economic, environmental and social factors and we finally present the different structures of the network when the importance of these factors alters. The proposed method scans through all the possible combinations of weights assigned to each criterion, providing an objective analysis in the absence of a panel of experts that would provide weights or a relative importance table with the application of AHP. Each combination is examined in terms of pre-set inputs and outputs taken from the slack variables and Data Envelopment Analysis (DEA) technique is applied.

The concept of constructing the renewable energy map of Greece using a 0-1 Weighted Goal Programming model and utilizing DEA models as a filter to select the best out of multiple solutions, has not been proposed before.

The paper is structured as follows. In Section 2, we present the related literature review. In Section 3 we present the proposed modeling framework. In Section 4 we present and analyze the results of the analysis. Finally, a summary of the proposed approach is demonstrated in Section 5 while Conclusions are presented in Section 6.

## 2. Literature review

The use of goal programming has so far become popular with numerous applications to the energy sector, by solving problems related to energy production and consumption, gas emissions and other subproducts of the related procedures, economic and public welfare. Particularly, goal programming has been also applied to problems related to energy networks' design.

The multicriteria decision making applications in energy planning vary, encountering multiobjective optimization, decision support systems and multicriteria decision making methods. Among the most common methods in the literature we found AHP, PROMETHEE, ELECTRE, MAUT, fuzzy methods and decision support systems (DSS) [5] [6] [7]

Afgan and Carvalho [8], presented a framework for the selection of new renewable energy plants considering installation cost, energy system efficiency and sustainability, environmental criteria ($CO_2$ production) and social assessment. The main objective of the study was to define the major energy indicators which are used in the appraisal and selection of sustainable energy systems. Aras et al [9] approached the problem of choosing the most efficient location for Wind Observation Station (WOS) applying the analytic hierarchy process (AHP).

A multiobjective linear programming model dealing with economic, energy and environmental interaction was presented by Oliveira and Antunes [10]. The proposed model could be applied to problems considering the optimization in power production, self-power generation, employment effects, gas emissions and energy imports and revealed the existence of strong antagonism between a) economic growth and social welfare and b) energy production, energy imports and environmental impacts.

Another model that supports sustainable energy system management under uncertainty is IMIF-EP inexact mixed-integer fractional energy system planning and was presented by

Zhu et al [11]. The proposed model studied the power generation expansion planning and considered issues related to sustainability enclosing systems' complexities, uncertainties and dynamics.

In Greece the problem of energy mapping has so far been examined in both regional and national level. In regional level analysis, the research is focused on islands. Koroneos et al [12] proposed the optimal energy network design based on RES in the Greek island of Lesvos, applying a multiobjective optimization methodology taking into account environmental, energy consumption, cost and resource constraints. Similarly, the optimal use of different RES (wind energy, solar energy and biomass energy sources) in the Greek island of Lemnos in order to accomplish the local energy needs was the principal object of Koroneos et al [13] study, regarding a variety of environmental, financial and social criteria.

Palaiologou et al [14] performed a research using GIS and WAsPand recording the wind characteristics and the weather pattern of the Greek island of Lesvos; the main objective of this study was the identification of island's wind production potentials. A similar analysis has been performed for a wind resource analysis in conjunction with a spatial and economic analysis to discover the optimum solution for the wind utilization in Kythira island, Greece [15].

Mourmouris et al [16] applied a multicriteria decision analysis technique in order to describe the framework for the selection of the most suitable decision among all alternatives in energy planning and exploitation of RES for power and heat generation in the Greek island of Thassos. For the satisfaction of the island's energy needs economic, environmental, social and technological criteria was considered and the REGIME method was applied, which is a partially compensatory method allowing compensation among the set criteria. Mourmouris et al [16] have also applied a REGIME based method to Samothrace Island in Greece with respect to the optimal exploitation of RES in the island, comparing among P/V plants, wind plants and a mix of wind – P/V plants.

The RES potential (wind parks) in the Dodecanese Islands was approached by identifying the major barriers in their application: technological, environmental, social, economic and regulatory, administrative and legislative [17]. In this study the EMERGENCE 2010 methodology was applied in order to select the location of the wind parks in the group of islands in order to satisfy the local energy needs based on the above criteria.

By applying NREL's HOMER method which evaluates energy power systems Giatrakos et al [18], proposed a redesigning of the energy system at the Greek island of

Karpathos. The proposed allocation of the renewable energy plants was presented by promoting the most sustainable scenario.

The multicriteria methodology application is also used by Tsoutsos et al [19] in proposing the sustainable energy planning for the Greek island of Crete. The choice of renewable energy plants' installation in the island was made based on the PROMETHE model considering economic, technical, social and environmental criteria. The sustainable power planning of Crete was also explored by applying the RETscreen International Clean Energy Project Analysis suite, considering the energy production, life-cycle costs and GHG emissions reduction of renewable energy plants and technologies [18].

Besides the regional studies on RES and energy mapping and applications, also research in a national level has been conducted. Kalampalikas et al [20] [21] studied the expansion in the Greek electricity production system focused on three different orientations: energy, environmental and economic. Furthermore, they investigated the way in which RES affect the expansion of the network, applying WASP-IV, revealing that several renewable energy plants should be built in order to achieve the EU20 goals. Additionally, Kambezidis [22] proposed a policy mix for achieving the aforementioned goals, using a variety of models and methods such as the Green-X simulation model and multi-criteria AHP, MAUT and SMART methods.

A large scale analysis of the integration of the renewable energy sources in the Greek power sector was also performed by Voumvoulakis et al [23]. The analysis concluded that the Greek electricity sector in order to achieve the EU20 goals should be radically transformed; the existing plants should be replaced by two to six new CCGT plants (850–2550 MW) and one new lignite plant (400 MW).

The capacity expansion of the Greek interconnected electric system in the pursuit of the EU20 goals has also been studied applying Long range Energy Alternatives Planning Systems (LEAP), which enables the presentation of the results from the different proposed strategies, rather than leading to the optimum alternative [24]. The study proposed five different scenarios in the supply and energy demand based on the technological (TD) and economic development (ED) (reference, slowed ED and TD, slow ED and fast TD, accelerated ED and slow TD, accelerated ED and fast TD) and explored the economic and environmental effects in conjunction with energy efficiency. The results revealed that the mix of the energy plants and the electricity generation per technology type vary among the different scenarios; finally the study highlighted that the EU20 goals could be achieved only under an accelerated economic development and the application of advanced RES technologies.

Similarly, national researches focusing on energy system construction based on RES have been conducted in other European Countries. San Cristóbal [25] developed a goal programming model for locating five different renewable energy plants in the region of Cantabria in the North of Spain, considering the fulfillment of seven different goals, related to energy production, the distance between the plants, the investment, operation and maintenance costs, the gas emissions, the number of created jobs and citizens' acceptance.

Likewise, an application of the ELECTRE method to energy planning in Sardinia was presented by Beccali et al [26] parleying three scenarios: environmental oriented, economy oriented and energy saving – rationalization scenario. The selection among fourteen different renewable energy sources was examined and the study revealed that there was a significant variation of the overall choices among the scenarios.

Other studies explore the impact of renewable energy technologies applications focus on employment effects [27], public attitude and social acceptance [28] [29] [30] [31] and environmental impacts [32] [33] [34]. The economic viability of hydro electricity production plants is demonstrated from the aspect of market analysis [35] [36], production planning [37], and for electricity energy production [38], using stochastic programming. The concept of integrating efficiency and location allocation analysis, has been presented in the context of health care [39]. Finally, in the literature we also find other approaches to such problems which differ from multicriteria decision making applications [40].

As we notice from the relative literature review, there are plenty of suggested models and applications to the energy sector that deal with energy production and energy networks' design. At the same time, it is also obvious that besides the numerous works there is still a variety of unanswered questions and variables which have not been considered so far. In Greece, most of the studies concern local energy needs and are focused on islands; thus in their majority they deal with specific types of renewable energy plants and avoid the possible combinations. Moreover, at the studies which take into account the country as a whole we observe the lack of a proposal for the design of the Greek renewable energy power production network, concerning the regional attributes in social, economic and environmental terms. In the international literature, studies concerning the national power production network design have been conducted; however the absence of the regional variables and the disregarding of the networks' efficiency are noticed. The current study aims to fill the gaps in the literature by proposing a model for the design of the Greek renewable energy production network with several types of renewable energy plants considering the social, economic and environmental attributes of the different regions and Greece as a whole. Moreover, the efficiency of the proposed model is also a point of research, adding to the study a point of differentiation and novelty.

The proposed model is a hybrid 0-1 weighted Goal Programming, DEA analysis model. The advantage of this kind of formulation is that the RES plant network is constructed in an optimized way, integrating the characteristics based on three major criteria; the economic, the environmental and the social. The weights placed on each of the criterion used, are not derived based on a questionnaire approach or a panel of experts and all combinations of weights are assigned to each criterion. Based on this approach, the Pareto front is constructed and DEA technique is employed as an outranking method. A DEA model that takes into account “good” and “bad” outputs is deployed and a comparison is performed with the conventional DEA envelope model. Through this analysis, it can be evaluated how the distribution of weights are assigned in order to get the most efficient solution. A Super-Efficiency model is then employed in order to reduce the solutions as much as possible.

## 3. Introduction to mathematical formulation

Renewable energy is considered to be a clean energy form due to the low levels of hazardous and GHG gas emissions like $CO_2$ and $NO_x$. There is a noticeable switch to electrical energy production from renewable power plants in the recent years. This switch is attributed to country’s economic crisis and on environmental directives (like Kyoto protocol and EU environmental directives).

Yet, even in the case of producing this kind of clean energy, several tradeoffs should be taken into account. Those dilemmas often concern the perception of local communities, e.g. towards the installation of a wind farm from an aesthetical or environmental point of view. However, when speaking from an economic or environmental point of view, it should be determined what would be a surrogate measure for each of these criteria. The proposed work is designed in Greece, a country of rich renewable energy resources (wind, sun, rivers). Based on a wind speed data map of Greece in the mainland, the wind speed values are very low comparing to the coastal part of Greece or to the islands where wind speed values may be up to 20m/s [41]. Due to the special geographical position and ground morphology which consists of mainly mountainous areas with rivers and quite limited area of flat plain for cultivation a mathematical model should be examined, that would take all these factors into account.

In order to design the energy mapp of Greece a 0-1 weighted goal programming model is presented considering economic, environmental criteria. The criteria set a priori concern the following [42] [25]:

a) Power production of each renewable energy plant (Solar, Wind, Hydro and Biomass)
b) Investment Ratio
c) Operation and Maintenance costs
d) Operating Hours
e) Tons of $CO_2$ avoided ($tCO_2/yr$)
f) Jobs created
g) Unemployment
h) GDP

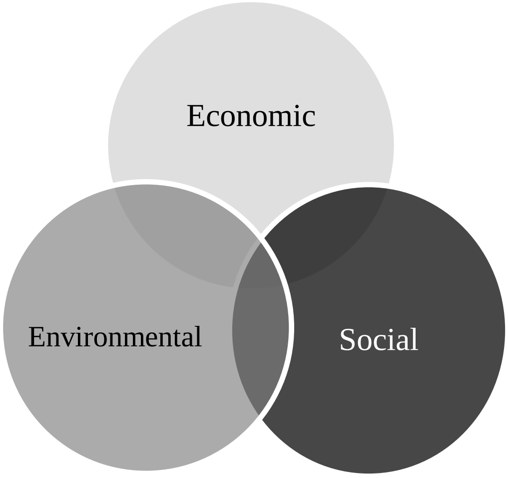


**Figure 1** Basic pylons of the renewable energy design

The aforementioned goals are grouped into three major pylons as seen in Figure 1. The economic pylon contains the power produced as a means of revenue, the investment ratio, operating and maintenance cost and operating hours. The environmental aspect contains the annual tonnes of $CO_2$ avoided by the installation of a renewable plant and the social pylon consists of the jobs created, the unemployment percentage and GDP.

From the above criteria, criteria (a), (b), (c) and (d) are characterized Economic, criterion (4) as Environmental and finally criteria (f), (g) and (h) as Social. Greece has 51 prefectures where each renewable energy plant can potentially be installed.

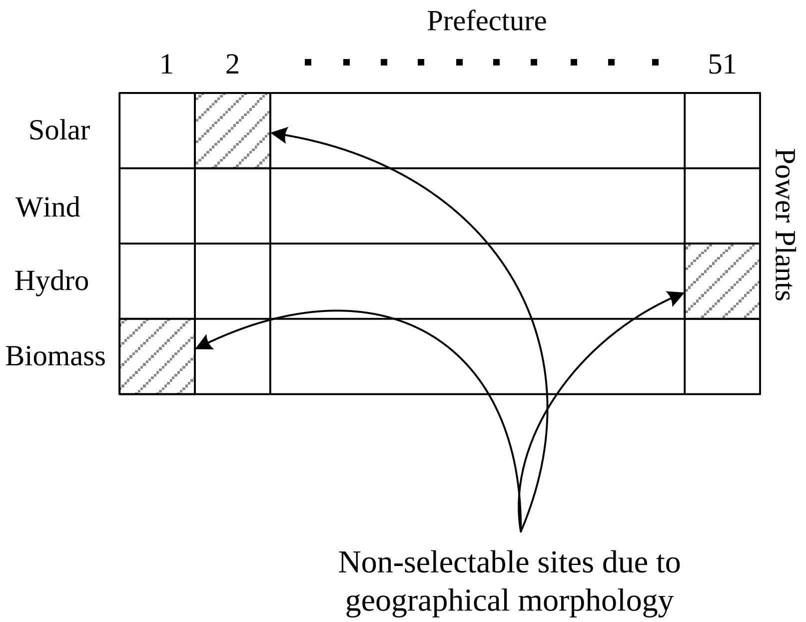


**Figure 2** Exclusion rules for the possible installation of Renewable Power Plants in each Prefecture.

Designing the renewable energy map of a country with a lot of meteorological and geographical contradictions is not an easy task. In previous studies the design of renewable energy map has been done based on subjective criteria (people's perceptions, expert's interviews etc). In this work, in order to provide a realistic approach for the renewable energy map of Greece, exclusion rules of each plant are predetermined, based on the objective criteria (geographical topography of the prefecture and non-existence of the renewable form of energy) as it can be seen in Figure 2. The sites for location for each type of renewable energy plant, have been based on technical reports or previous techno-economic analyses. Furthermore, in order to capture the social characteristics of each prefecture, the unemployment percentage and GDP have been introduced.

### 3.1 The proposed 0-1 Weighted Goal Programming model

In order to model the assignment of a renewable plant $i$ to prefecture $j$, binary variables $X_{ij}$ are introduced. The set of selectable sites for each renewable plant and each prefecture is graphically presented in Table 1 where the potentially selected locations are denoted with the shaded cell whereas a blank cell indicates that there is not a matching between renewable energy plant and of that specific prefecture.

| Plant | Prefecture | Drama | Kavala | Evros | Xanthi | Rodopi | Imathia | Thessaloniki | Kilkis | Pella | Pieria | Serres | Chalkidiki | Grevena | Kastoria | Kozani | Florina | Arta | Thesprotia | Ioannina | Karditsa | Larissa | Magnisia | Trikala | Zachinthos | Corfu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | Wind power P<5MW | ▨ |  | ▨ | ▨ | ▨ |  |  | ▨ |  |  | ▨ |  |  |  | ▨ | ▨ |  | ▨ |  |  |  | ▨ |  |  | ▨ |
| A2 | Wind power 5< P< 10MW | ▨ |  | ▨ | ▨ | ▨ |  |  | ▨ |  |  | ▨ |  |  |  | ▨ | ▨ |  | ▨ |  |  |  | ▨ |  |  | ▨ |
| A3 | Wind power 10< P< 50MW | ▨ |  | ▨ | ▨ | ▨ |  |  | ▨ |  |  | ▨ |  |  |  | ▨ | ▨ |  | ▨ |  |  |  | ▨ |  |  | ▨ |
| A4 | Hydroelectric P< 10MW |  |  |  |  |  |  |  |  |  |  |  |  |  |  | ▨ |  |  | ▨ | ▨ | ▨ |  |  | ▨ |  |  |
| A5 | Hydroelectric 10<P< 25MW |  |  |  |  |  |  |  |  |  |  |  |  |  |  | ▨ |  |  | ▨ | ▨ | ▨ |  |  | ▨ |  |  |
| A6 | Hydroelectric 25< P< 50MW |  |  |  |  |  |  |  |  |  |  |  |  |  |  | ▨ |  |  | ▨ | ▨ | ▨ |  |  | ▨ |  |  |
| A7 | Solar Thermo-electric P <10MW |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | ▨ | ▨ |  | ▨ | ▨ |
| A8 | Biomass (energetic cultivations) P <5MW | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |  | ▨ | ▨ |  | ▨ | ▨ | ▨ | ▨ | ▨ |  |  |
| A9 | Biomass (forest and agricultural wastes) P >5MW | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |  | ▨ | ▨ |  | ▨ | ▨ | ▨ | ▨ | ▨ |  |  |
| A10 | Biomass (farming industrial wastes) P<5MW | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |  | ▨ | ▨ |  | ▨ | ▨ | ▨ | ▨ | ▨ |  |  |
| A11 | Biomass (forest industrial wastes) P >5MW | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |  | ▨ | ▨ |  | ▨ | ▨ | ▨ | ▨ | ▨ |  |  |
| A12 | Biomass (co-combustion in conventional central) P> 50MW | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |  | ▨ | ▨ |  | ▨ | ▨ | ▨ | ▨ | ▨ |  |  |
| A13 | Bio fuels P <2MW | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |  | ▨ | ▨ |  | ▨ | ▨ | ▨ | ▨ | ▨ |  |  |

| Plant | Prefecture | Keffalonia | Lefkada | a | Achaia | Ilia | Viotia | Evia | Euritania | Fthiotida | Fokida | Attica | Argolidos | Arkadia | Korinthia | Lakonia | Mesinia | Lesvos | Samos | Chios | Dodekanisa | Kiklades | Iraklio | Lasithi | Rethimno | Chania |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | Wind power P<5MW | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |  |  |  |  |
| A2 | Wind power 5< P< 10MW | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |  |  |  |  |
| A3 | Wind power 10> P> 50MW | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |  |  |  |  |
| A4 | Hydroelectric P< 10MW |  |  |  | ▨ | ▨ |  |  | ▨ |  |  |  |  | ▨ | ▨ | ▨ |  |  |  |  |  |  |  |  |  |  |
| A5 | Hydroelectric 10> P> 25MW |  |  |  | ▨ | ▨ |  |  | ▨ |  |  |  |  | ▨ | ▨ | ▨ |  |  |  |  |  |  |  |  |  |  |
| A6 | Hydroelectric 25< P< 50MW |  |  |  | ▨ | ▨ |  |  | ▨ |  |  |  |  | ▨ | ▨ | ▨ |  |  |  |  |  |  |  |  |  |  |
| A7 | Solar Thermo-electric P <10MW | ▨ | ▨ |  |  |  | ▨ | ▨ |  |  |  |  | ▨ |  | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| A8 | Biomass (energetic cultivations) P <5MW |  |  | ▨ |  | ▨ |  | ▨ |  |  |  |  |  | ▨ |  |  |  |  |  |  |  |  |  |  |  |  |
| A9 | Biomass (forest and agricultural wastes) P >5MW |  |  | ▨ |  | ▨ |  | ▨ |  |  |  |  |  | ▨ |  |  |  |  |  |  |  |  |  |  |  |  |
| A10 | Biomass (farming industrial wastes) P<5MW |  |  | ▨ |  | ▨ |  | ▨ |  |  |  |  |  | ▨ |  |  |  |  |  |  |  |  |  |  |  |  |
| A11 | Biomass (forest industrial wastes) P >5MW |  |  | ▨ |  | ▨ |  | ▨ |  |  |  |  |  | ▨ |  |  |  |  |  |  |  |  |  |  |  |  |
| A12 | Biomass (co-combustion in conventional central) P> 50MW |  |  | ▨ |  | ▨ |  | ▨ |  |  |  |  |  | ▨ |  |  |  |  |  |  |  |  |  |  |  |  |
| A13 | Bio fuels P <2MW |  |  | ▨ |  | ▨ |  | ▨ |  |  |  |  |  | ▨ |  |  |  |  |  |  |  |  |  |  |  |  |

**Table 1 :** Allowable positions for each renewable energy plant at each prefecture

Based on Table 1, the set of potentially installed renewable plants ( $S$ ) is constructed. The corresponding constraints are introduced below.

$$X_{ij} = 0, \quad \forall i, j \in \Omega / S \qquad (1)$$

$$\sum_{i \in S} X_{ij} \leq 1, \quad \forall j \in S \tag{2}$$

$$\sum_{j \in S} X_{ij} \geq 1, \quad \forall i \in S \tag{3}$$

$$\sum_{i,j \in S} X_{ij} \leq K \tag{4}$$

$$\sum_{i,j \in S} X_{ij} \geq 1 \tag{5}$$

As shown in Table 1, each renewable plant can be potentially installed in specific prefectures based on previous techno-economic analysis or reports. In constraint (1), $\Omega$ is the set of all possible combinations and contains $|I| \times |J|$ elements whereas $S$ is the set of potentially installed plants. This constraint is introduced to exclude the selection of renewable plant $i$ to prefecture $j$ by forcing binary variable $X_{ij}$ to become zero, for that certain combination that belongs to the non-selectable set ($\Omega / S$). Applying the constraints to only the possible selected prefectures/sites, reduced significantly the complexity of the model as the final model contains $|I| \times |J| - |\Omega / S|$ binary variables.

In Figure 3, the correspondence of the possible set of RES plants is shown. As it can be seen, wind power plants, which consist of alternatives A1 – A3, can be installed in Northern-East Greek Prefectures, Peloponnese and Aegean islands (Lesvos prefecture, Cyclades and Dodecanese) according to Figure 3a). Based on Figure 3b), the Hydroelectric alternatives (A4 – A6) can be installed in the mainland of Greece and in prefectures that have lakes, and artificial dams. Solar-Thermal alternative (A7) can be installed mostly in islands as it can be seen in Figure 3c) while Biomass and Biofuels, which use forest residues and industrial crops, alternatives (A8 – A13) can be installed also in the mainland and near large plains as that of Thessaly and Macedonia or near large mountainous areas with large forest areas (Figure 3d).

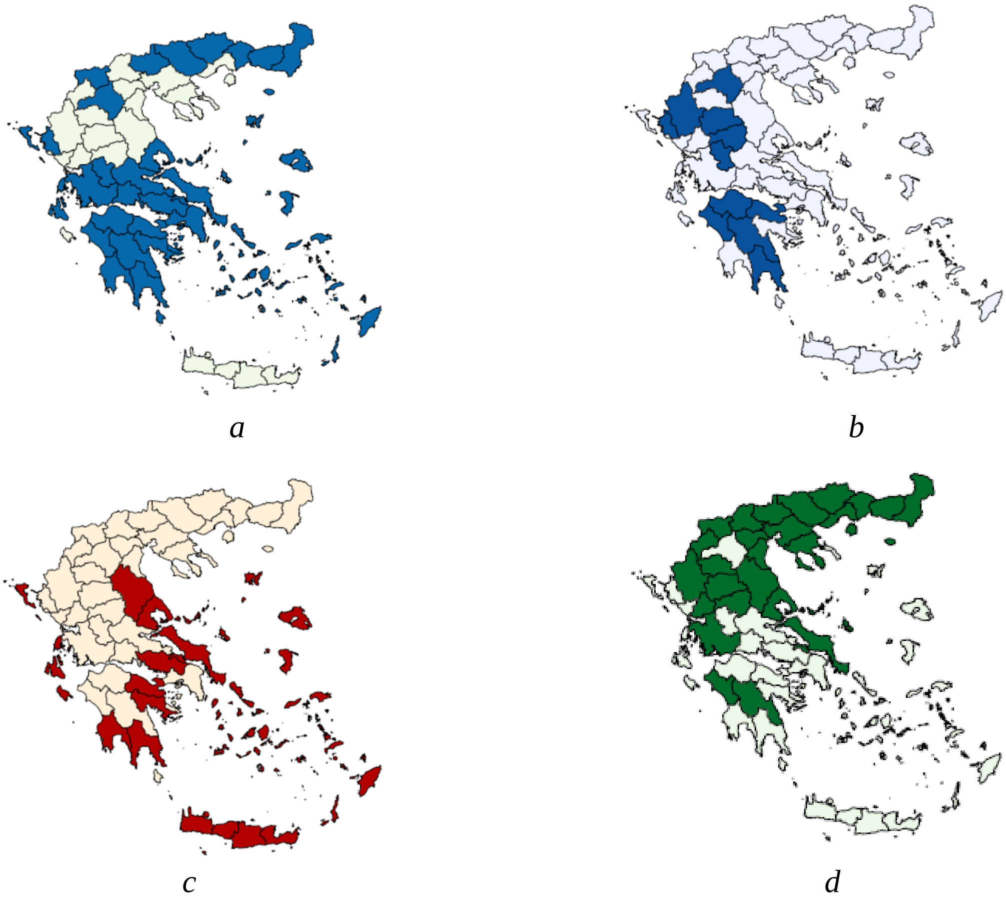


**Figure 3:** Possible locations of alternatives per category; a) Wind, b) Hydroelectric, c) Solar-Thermal and d) Biomass and Biofuels

The renewable energy plants installed should be equally dispersed in territory. Thus, in order to prevent the model to assign all the plants in a single prefecture, constraint (2) states that a single plant is selected at each prefecture.

In this work, each prefecture should be chosen more than once. Thus, constraint (3) is introduced to model the previous statement.

Overall in this analysis the total renewable plants and prefectures should be less than a certain number $K$ and larger than 1. In this analysis this number is set to 51, namely the selected combinations of renewable plants and prefectures must be at most 51.

$$\sum_{i,j \in S} PP_i \cdot X_{ij} + d_{PP}^{-} - d_{PP}^{+} = G^{PP} \tag{6}$$

$$\sum_{i,j \in S} CO_{2i} \cdot X_{ij} + d_{CO_2}^{-} - d_{CO_2}^{+} = G^{CO_2} \tag{7}$$

$$\sum_{i,j \in S} OH_i \cdot X_{ij} + d_{OH}^{-} - d_{OH}^{+} = G^{OH} \tag{8}$$

$$\sum_{i,j\in S} INV_i \cdot X_{ij} + d^{-}_{INV} - d^{+}_{INV} = G^{INV} \tag{9}$$

$$\sum_{i,j\in S} OM_i \cdot X_{ij} + d^{-}_{OMC} - d^{+}_{OMC} = G^{OM} \tag{10}$$

$$\sum_{i,j\in S} JOB_i \cdot X_{ij} + d^{-}_{JOB} - d^{+}_{JOB} = G^{JOB} \tag{11}$$

$$\sum_{i\in S} UMP_j \cdot X_{ij} + {}^{UMP}d^{-}_{j} - {}^{UMP}d^{+}_{j} = G^{UMP}_{j},\ \forall j \in S \tag{12}$$

$$\sum_{i\in S} GDP_j \cdot X_{ij} + {}^{GDP}d^{-}_{j} - {}^{GDP}d^{+}_{j} = G^{GDP}_{j},\ \forall j \in S \tag{13}$$

Constraint (6) models the goal of power production, (8) models the goal of operating hours, (9) models the goal of investment and (10) models the goal of operations and maintenance cost, forming the economic pylon of this analysis. The environmental pylon is formed by constraint (7) which models the annual tonnes of $CO_2$ avoided and finally, the social pylon is formed by constraints (11)-(13) which model the goals of jobs created, unemployment percentage and GDP. These aspects of the renewable energy design can be visualized in Table 2. First of all the power production goal should be maximized, as the installed plants must produce more power than the goal. The goal regarding $CO_2$ emissions should be also maximized, as with the installation of a renewable energy plant there is an environmental benefit. Regarding the investment of this venture the design should be implemented with the least cost. For this reason this goal should be minimized. The goals of operating hours and operation and maintenance cost should be maximized and minimized correspondingly based on previous reasoning. Regarding the social pylon of the study, the maximization of job goal is straightforward, yet in Table 2 the unemployment goal is maximized. The reasoning behind this selection is that the installation of a renewable plant in a prefecture with low unemployment would not help in a “social” way the country or the prefectures in particular. Similarly, the GDP goal should be minimized as high GDP is a measure of a prefecture with high income. It should be noted that in this work, the location of a renewable energy plant, is set based on objective data, provided by Hellenic Statistical Authority by the latest census. Furthermore, as there is no point for the latter two goals to be treated aggregated, the goal for unemployment and GDP is assigned to each prefecture. Also, in Tables 3 and 4, the data for the coefficients of goal constraints (6) – (13) are presented; the data presented in Table 3 are based on [42] while the data presented in Table 4 presenting GDP and unemployment per prefecture, are based on Hellenic Statistical Authority.

Main target of this analysis is to propose the optimal design of renewable energy plants using a 0-1 Weighted Goal Programming (WGP) model [43] [44]. The advantage of this technique is that multiple and conflicting objectives can be taken into account.

**Table 2** Goals and aspects

| | **Parameter** | **Direction** | **Goal** | **Value** | **Unit** | **Aspect** |
|---|---|---|---|---|---|---|
| Power Production | $PP$ | $\geq$ | $G^{PP}$ | $500,000$ | MW | Economic |
| $CO_2$ emissions avoided | $CO_2$ | $\geq$ | $G^{CO2}$ | $53,243$ | Tones | Environment |
| Investment | $INV$ | $\leq$ | $G^{INV}$ | $16 \cdot 10^9$ | €/KW | Economic |
| Operating Hours | $OH$ | $\geq$ | $G^{OH}$ | 20,000 | hrs | Economic |
| Op. & Maint. Cost | $OMC$ | $\leq$ | $G^{OM}$ | 500,000 | € | Economic |
| Jobs | $JOB$ | $\geq$ | $G^{JOB}$ | 500 | ppl | Social |
| Unemployment per prefecture | $UMP$ | $\geq$ | $G_j^{UMP}$ | 20 | % | Social |
| GDP per prefecture | $GDP$ | $\leq$ | $G_j^{GDP}$ | $12,500$ | €/ppl | Social |

**Table 3** Data for the parameters regarding environmental, economic and social aspects.

| **Plants (Alternatives)** | **PP (MW)** | **$CO_2$ (Tones)** | **INV (€/KW)** | **OH (hours)** | **OMC (€)** | **JOB (ppl)** |
|---|---|---|---|---|---|---|
| A1 | 5,000 | 1,929,936 | 937 | 2,350 | 1,470 | 15 |
| A2 | 10,000 | 3,216,560 | 937 | 2,350 | 1,470 | 15 |
| A3 | 25,000 | 9,649,680 | 937 | 2,350 | 1,510 | 15 |
| A4 | 5,000 | 472,812 | 1,500 | 3,100 | 1,450 | 8 |
| A5 | 2,000 | 255,490 | 700 | 2,000 | 700 | 8 |
| A6 | 3,500 | 255,490 | 601 | 2,000 | 600 | 12 |
| A7 | 5,000 | 482,856 | 5,000 | 2,596 | 4,200 | 10 |
| A8 | 5,000 | 2,524,643 | 1,803 | 7,500 | 7,106 | 15 |
| A9 | 5,000 | 2,524,643 | 1,803 | 7,500 | 5,425 | 15 |
| A10 | 5,000 | 2,524,643 | 1,803 | 7,500 | 5,425 | 15 |
| A11 | 5,000 | 2,524,643 | 1,803 | 7,500 | 2,813 | 15 |
| A12 | 56,000 | 4,839,548 | 856 | 7,500 | 4,560 | 20 |
| A13 | 2,000 | 5,905,270 | 1,503 | 7,000 | 2,512 | 15 |

**Table 4** Data for the parameters Unemployment (UMP) and GDP.

| **Prefecture** | **GDP (€/ppl)** | **Unemployment (%)** | **Prefecture** | **GDP (€/ppl)** | **Unemployment (%)** |
|---|---|---|---|---|---|
| Drama | 10,842.38 | 36.8 | Kefallonia | 18,575.59 | 20.5 |
| Kavala | 14,889.36 | 22.8 | Levkas | 14,649.55 | 20.5 |
| Evros | 14,717.30 | 22.0 | Aitolia and Akarnania | 12,149.65 | 25.5 |
| Xanthi | 12,432.47 | 37.5 | Achaia | 16,324.26 | 37.6 |
| Rodopi | 12,677.10 | 16.8 | Ilia | 11,711.18 | 15.0 |
| Imathia | 12,427.15 | 27.4 | Viotia | 26,892.34 | 23.8 |
| Thessaloniki | 16,145.26 | 32.1 | Euvoia | 14,764.05 | 29.7 |
| Kilkis | 12,211.71 | 33.2 | Evrytania | 11,142.51 | 29.7 |
| Pella | 12,659.01 | 25.9 | Fthiotida | 14,356.57 | 29.7 |
| Pieria | 12,719.08 | 29.0 | Fokida | 11,766.18 | 30.2 |
| Serrai | 10,360.47 | 22.9 | Attiki | 25,224.24 | 28.2 |
| Chalkidiki | 15,199.83 | 22.4 | Argolida | 15,109.45 | 24.7 |
| Grevena | 11,796.14 | 33.7 | Arkadia | 16,988.94 | 24.9 |
| Kastoria | 11,363.58 | 33.7 | Korinthos | 17,751.96 | 21.7 |
| Kozani | 22,014.42 | 35.0 | Lakonia | 11,958.30 | 15.0 |
| Florina | 20,796.46 | 21.4 | Messinia | 13,653.60 | 24.5 |
| Arta | 11,721.44 | 34.8 | Lesvos | 14,625.89 | 20.9 |
| Thesprotia | 14,252.14 | 28.7 | Samos | 15,060.81 | 20.9 |
| Ioannina | 13,245.70 | 28.7 | Chios | 14,798.43 | 22.2 |
| Preveza | 12,584.96 | 20.4 | Dodekanese | 18,682.58 | 19.8 |
| Karditsa | 9,281.81 | 23.9 | Kyklades | 24,491.30 | 22.2 |
| Larisa | 14,165.33 | 22.1 | Heraklion | 16,235.19 | 24.4 |
| Magnesia | 15,480.23 | 37.4 | Lasithi | 16,334.01 | 14.2 |
| Trikala | 11,239.17 | 20.4 | Rethymnon | 16,105.63 | 27.6 |
| Zakynthos | 20,014.09 | 13.9 | Chania | 16,216.25 | 26.3 |
| Kerkyra | 17,114.56 | 20.5 | | | |

In the first case, the left hand side should exceed the goal for power production, thus the under achieving slack assigned to the less or equal direction ($d^-$) must be minimized. As mentioned above, the third goal should be minimized thus the surplus slack variable ($d^+$) is minimized. In case that the goal should equal to the right hand side, then both the deviational variables should be minimized ($d^- + d^+$).

**Table 5:** Weight categorization and corresponding weight range assigned to each criterion economic, environmental and social.

| Weight categorization | Range |
|---|---|
| L (Low) | [0, 0.15) |
| M (Medium) | [0.15, 0.66) |
| H (High) | [0.66, 1] |

Objective function (14) consists of the goals presented in Table 2, the slack variables and the weights assigned to each criterion. The ranges of these values are shown in Table 5.

$$\begin{aligned}&\min w_{ECON}\cdot\left(\frac{d_{PP}^{-}}{G^{PP}}+\frac{d_{INV}^{+}}{G^{INV}}+\frac{d_{OMC}^{+}}{G^{OMC}}+\frac{d_{OH}^{-}}{G^{OH}}\right)+w_{ENV}\cdot\frac{d_{CO_2}^{+}}{G^{CO_2}}+\\&w_{SOC}\cdot\left(\frac{d_{JOB}^{-}}{G^{JOB}}+\sum_{j\in S}\frac{{}^{UMP}d_j^{-}}{G_j^{UMP}}+\sum_{j\in S}\frac{{}^{GDP}d_j^{+}}{G_j^{GDP}}\right)\end{aligned} \tag{14}$$

In objective function (14), the variables that correspond to the over and under achievement of each goal are normalized, by diving with corresponding goal. To each term of the objective function, a weight is assigned such that:

$$w_{ECON}+w_{ENV}+w_{SOC}=1 \tag{15}$$

The weight restriction must be always sum to unity as the weights are determined in advance. Also the different networks created by each set of weights are the following:

$$net_{ij}^{w}=X_{ij}^{*},\ \forall i,j\in S \tag{16}$$

Overall the proposed 0-1 WGP model consists of objective function (14), goal constraints (6) – (13) and network constraints (1) – (5).

The decisions that the proposed 0-1 Weighted Goal Programming model provides concern:

1. The installation of renewable plant *i* in prefecture *j* (energy network)
2. The amount of over and under achievement for each goal.
3. The energy map network.

### 3.2 Solution’s efficiency as a meta-analysis filter of Pareto front

Changing the weights on the variables of the objective function will eventually lead to different representations of the renewable energy network and variations in the over and under achievement of each goal. This will eventually construct the Pareto front, which is the space of all possible solutions. In order to filter the solutions provided by the previous 0-1 Weighted Goal Programming model, different DEA techniques are employed.

There are 3 types of weights in the above model as seen in (15). It is assumed that there are 3 scales of importance assigned to each weight. In Table 2, the importance to each weight is shown.

If $n$ are the different scales of weights importance and $m$ represents the incremental step of the range of each weight, there are $m \cdot (n!)$ permutations and probably different solutions. In the absence of a Decision Maker (DM) that would provide the relative importance of each pylon of the study, each solution is treated as a DMU and a DEA output oriented model is considered. In this work, DEA technique is used as an outranking method [45]. The ranking of the solutions will be based on resulting efficiency of each solution. As there are 3 scales of importance there are 100× (3!)=600 solutions.

Let us consider $x_{w,in}$ the matrix of inputs and $y_{w,out}$ the matrix containing the outputs that will be used in DEA. The LP model is described in (17). Slack variables that correspond to goals that will be minimized serve as inputs while those that correspond to goals that will be maximized serve as outputs.

$$\begin{aligned}
&\max\ \varphi \\
&s.t. \\
&\sum_{w=1}^{m\cdot(n!)} \lambda_w \cdot x_{w,in} \le x_{o,in},\ \forall in \\
&\sum_{w=1}^{m\cdot(n!)} \lambda_w \cdot y_{w,out} \ge y_{o,out} \cdot \varphi,\ \forall out \qquad (17) \\
&\sum_{w=1}^{m\cdot(n!)} \lambda_w = 1 \\
&\lambda_w \ge 0,\ \forall w
\end{aligned}$$

Considering that the analysis has impacts on economic, environmental and social aspects, some outputs can be treated as desirable and undesirable outputs. The LP model that models this instance is presented as follows:

$$
\begin{aligned}
&\max\ \xi\\
&s.t.\\
&\sum_{w=1}^{m\cdot(n!)} \lambda_w \cdot x_{w,in} \le x_{o,in},\ \forall in\\
&\sum_{w=1}^{m\cdot(n!)} \lambda_w \cdot y_{w,out} \ge y_{o,out}^{des} \cdot (1+\xi),\ \forall out\\
&\sum_{w=1}^{m\cdot(n!)} \lambda_w \cdot y_{w,out} \le y_{o,out}^{und} \cdot (1-\xi),\ \forall out\\
&\lambda_w \ge 0,\ \forall w
\end{aligned}
\tag{18}
$$

In LP model (17) $x_{w,in}$ is a 600×2 matrix of inputs and $y_{jr}$ is a 600×4 in the following form:

$$
x_{w,in} = \left[\begin{array}{cc} in=1 & in=2 \\ d_{INV}^{+} & d_{OMC}^{+} \\ & \end{array}\right] \tag{19}
$$

$$
y_{w,out} = \left[\begin{array}{cccc} out=1 & out=2 & out=3 & \overbrace{\hphantom{\left(d_{UMP}^{-}\right)^{-1}}}^{out=4} \\ d_{PP}^{-} & d_{JOB}^{-} & d_{OH}^{-} & \left(d_{UMP}^{-}\right)^{-1} \\ & & & \end{array}\right] \tag{20}
$$

In the case where $d_i^-$, $d_i^+$ =0 then a very small positive number $\varepsilon$ is assigned, where $\varepsilon \simeq 10^{-3}$ [46]. Based on LP model (17), the extracted efficiency will be computed upon the inputs and outputs of the study. A common measure to measure efficiency is Technical Efficiency (*TE*) which is defined as the reciprocal of $\varphi$, yielding a value in the range of $[0,1]$; DMUs with *TE*=1 are called fully technical efficient, while DMUs with *TE*<1, technically inefficient.

In terms of the LP model (18) [47] which is introduced to model the desirable and undesirable outputs, the unified score in this case is calculated as follows:

$$
\theta = 1 - \xi \tag{21}
$$

When applying LP model (18), outputs (20) change to desirable and undesirable as follows:

$$\begin{aligned} y^{des}_{w,out} &= \begin{bmatrix} out=1 & out=2 & out=3 \\ d^{-}_{PP} & d^{-}_{JOB} & d^{-}_{OH} \\ & & \end{bmatrix} \\ y^{und}_{w,out} &= \begin{bmatrix} out=1 \\ d^{-}_{UMP} \\ \end{bmatrix} \end{aligned} \tag{22}$$

In case where the value of $\xi = 0$ implies full efficient solution whereas if $\xi \neq 0$, the solution is inefficient. The inputs and outputs for the second stage analysis depicted here are the ones that show a big fluctuation based over the different runs.

### 3.3 Super efficiency

In order to evaluate the best out of all the possible combinations of inputs and outputs, a Super-Efficiency model is employed. Based on this approach, the super-efficiency of the DMU under investigation is extracted from the analysis. Thus, the efficiency that will be produced will exceed 1, however this DEA model may yield infeasible solutions depending on the dataset provided. The mathematical formulation of Super-Efficiency DEA model is the following [48]:

$$\begin{aligned} &\min\ \theta^{S} \\ &s.t. \\ &\sum_{\substack{w=1 \\ w\neq o}}^{m\cdot(n!)} \lambda_w \cdot x_{w,in} \leq \theta^{S} \cdot x_{o,in},\ \forall in \\ &\sum_{\substack{w=1 \\ w\neq o}}^{m\cdot(n!)} \lambda_w \cdot y_{w,out} \geq y_{o,out},\ \forall out \\ &\lambda_w \geq 0,\ \forall w \end{aligned} \tag{23}$$

In formulation (23), $\theta^{S}$ measures super-efficiency whereas the rest of the formulation remains the same as (17), with the exception of the summation that does not calculate the DMU under investigation for each run of the LP model.

## 4. Results

The results of the work mostly focus on the outranking of solutions and the investigation of the mapping of renewable energy plants. Based on the efficiency scores, the weights placed on each of the pylons of the study, which are modeled by slack variables on the objective function, are examined. The efficiency scores of the analysis are presented in next figure (Figure 4).

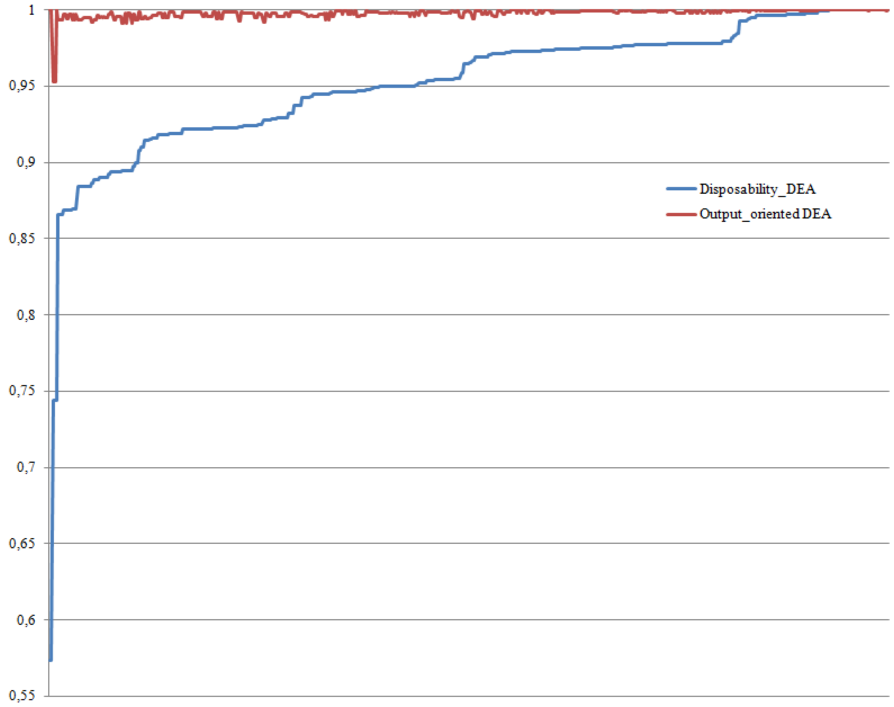


**Figure 4:** Efficiency scores under the two examined DEA technologies.

As it can be seen from Figure 4, the disposability DEA model identifies the discrimination between the efficiency of solutions. On the contrary, the classical DEA model provides higher efficiency scores to the solutions. From the analysis it can be identified that a fully efficient score can be achieved with many combinations of weights. An analytical discussion will be performed for all of these combinations of weights.

Under disposability model, 39 cases of fully technical efficient solutions were identified. Out of the total instances, 4 (10.25%) belong to the interval of weights that are higher on the social criterion, medium to the environmental criterion and very little importance on the economic criterion. Also, 6 instances (15.38%) yield a fully efficient solution when the importance is higher on the environmental criterion, medium on the economic and low on the social. Overall, fully efficient scores are obtained by taking into account higher values on the economic criterion 35% of all the instances, for the environmental criterion 35% of the instances and only 25% on the social criterion. In Figure 5, a general direction of the weights that are assigned to each criterion in order to get the most efficient solutions. As it can be seen, in the majority of the cases, the social criterion is weighted in the range of medium [0.15 – 0.66) and high values [0.66 – 1], the environmental criterion in the range of low [0 – 0.15) and medium [0.15 – 0.66) values while the economic criterion in the range of low values. Quick outcomes of this finding is that the social acceptance of that large scale project and along with an environmental conscious design, are the key factors for the design of renewable energy plant of Greece.

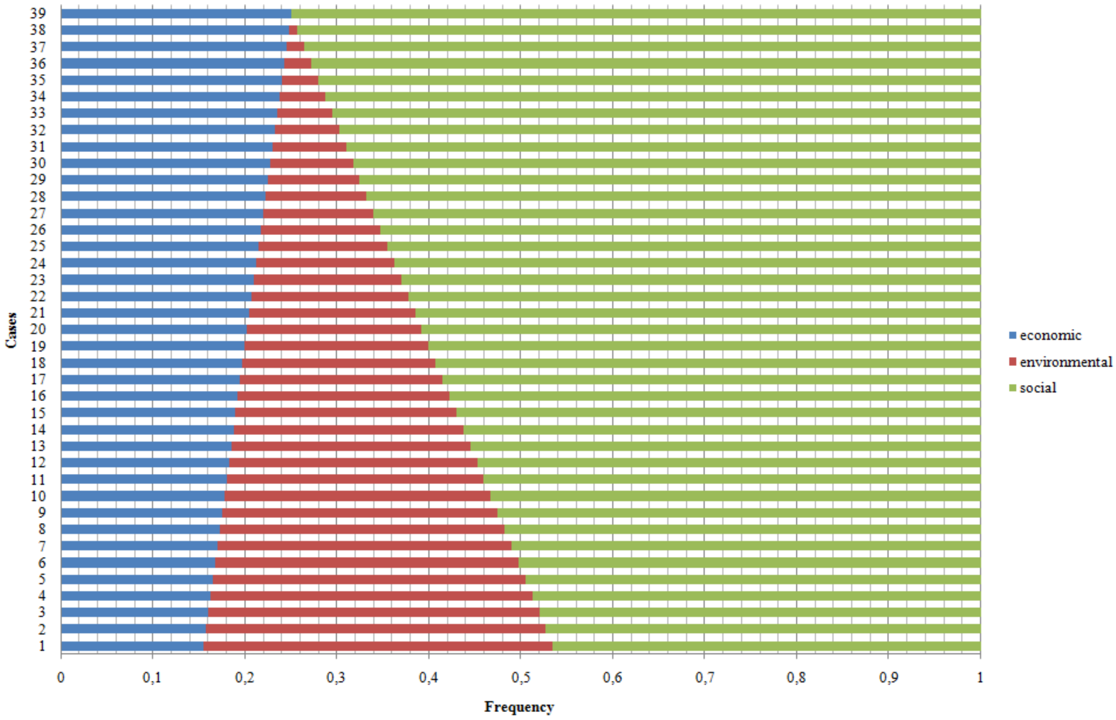
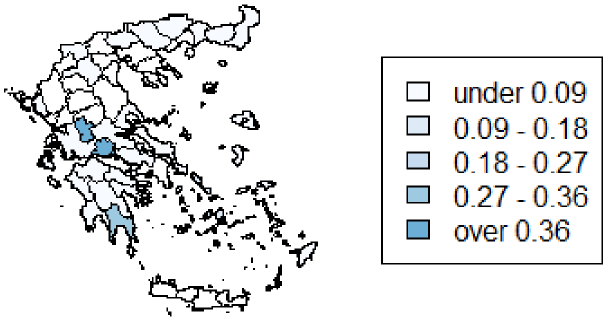


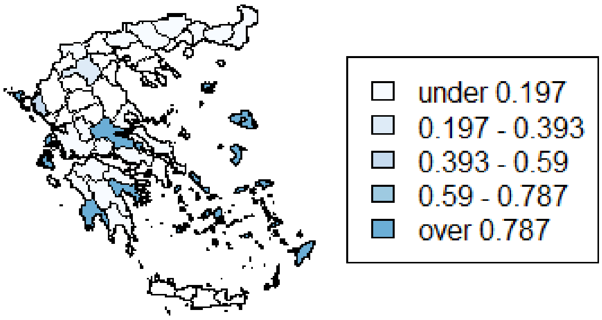
**Figure 5:** Frequency analysis of each weight towards economic, environmental and social criterion

The next step of the proposed analysis is the renewable energy map for all representations of weight importance in the objective function. The representations of all networks have been stored in a matrix for all the iterations, namely $net_{ij}^{w}$. Summing over all the representations of networks $\left( \sum_{w=1}^{W} net_{ij}^{w} \Big/ |W| \right)$ the following figure (Figure 6) represents the probability of installation of alternative *i* to prefecture *j*.

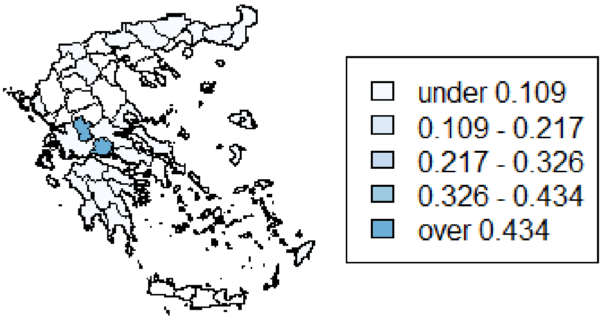
From Figure 6, it can be seen that alternative A1 (Wind power<5MW) has larger probability of installation in Evritania, Fokida and Lakonia, which are mostly mountainous prefectures as seen in Figure 6a). Regarding alternative A2 (Wind power 5<P<10MW), the largest probability of occurrence is that of Corfu, Kefallonia, Lefkada, Cyclades, Dodekanese, Argolida, Messinia, Fthiotida, and North Aegean islands (Lesvos, Chios, Samos). For alternative A2, mostly islands and mountainous regions have been selected. The probability of occurrence of A3 alternative (10<P<50 MW) is lower than that of A2, while the prefectures that would be selected are Evritania and Fthiotida. Altenatives A4, A5 and A6 which correspond to Hydroelectric power plants as shown in Table 1, have the largest probability of occurrence in Achaia, Kozani for A4, in Korinthia for A5 and only Kozani for A6. The alternative that corresponds to Solar-Thermo electric power plant, has higher probability of occurrence in Crete prefectures and Zakynthos. Regarding Biomass and Biofuels alternatives, A8 – A13 it can be seen that the largest probability of occurrence is shown for alternatives A12 where the higher probability of installation is in prefecture Rhodopi, Florina, Grevena, Drama, Imathia Chalkidiki, Serrai and Kilkis; for alternative A13, the highest probability for installation of a Bio fuels P <2MW, is found in Pieria, Achaia and Pella. In the study prefecture 20 (Preveza) has not been initially introduced in the study as from the techno-economic analysis where set *S* is constructed upon, no renewable plant could be sustainable. From the results of the Super-Efficiency DEA model, a super-efficiency of 1.1038 was achieved by two combinations. The first is when medium values are assigned to the economic criterion, low values to the environmental and high values to the social criterion while the second when low values are assigned to the economic criterion, medium values to the environmental and large values to the social criterion which enforces the previous finding regarding the direction of weights assigned to each criterion.


under 0.09
0.09 - 0.18
0.18 - 0.27
0.27 - 0.36
over 0.36

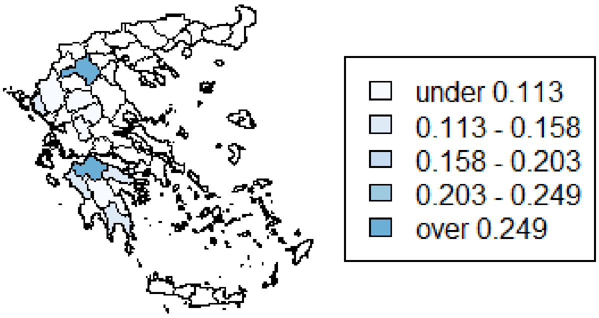
*a*


under 0.197
0.197 - 0.393
0.393 - 0.59
0.59 - 0.787
over 0.787

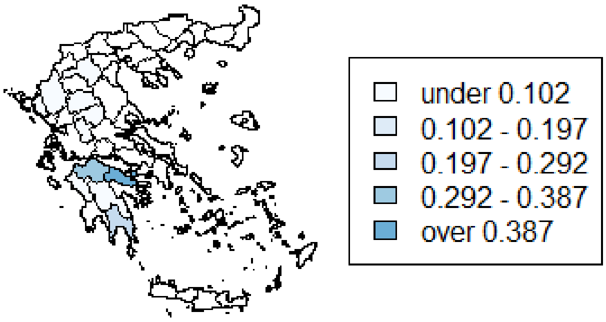
*b*


under 0.109
0.109 - 0.217
0.217 - 0.326
0.326 - 0.434
over 0.434

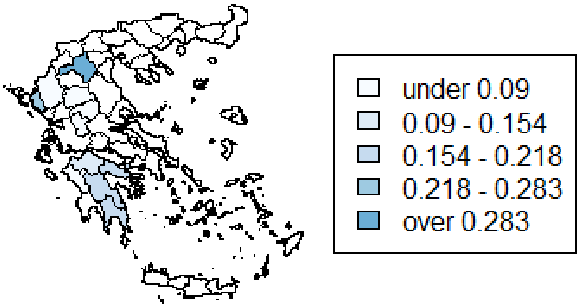
*c*


under 0.113
0.113 - 0.158
0.158 - 0.203
0.203 - 0.249
over 0.249

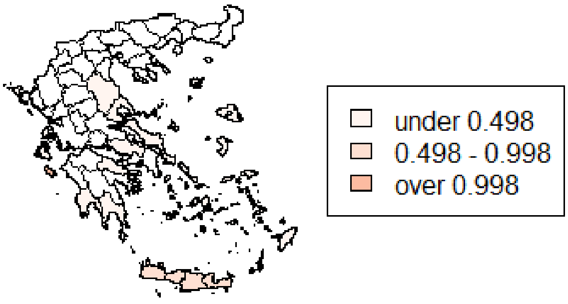
*d*


under 0.102
0.102 - 0.197
0.197 - 0.292
0.292 - 0.387
over 0.387

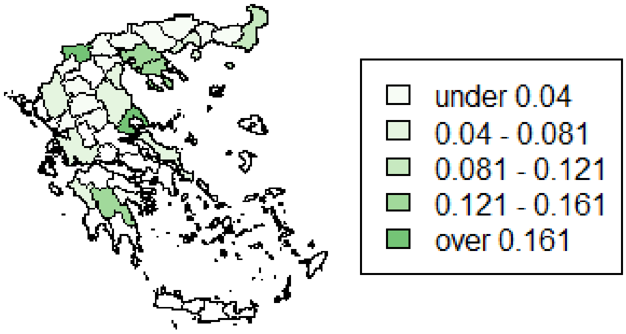
*e*


under 0.09
0.09 - 0.154
0.154 - 0.218
0.218 - 0.283
over 0.283

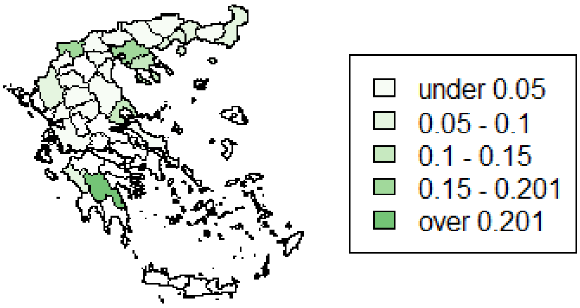
*f*


under 0.498
0.498 - 0.998
over 0.998

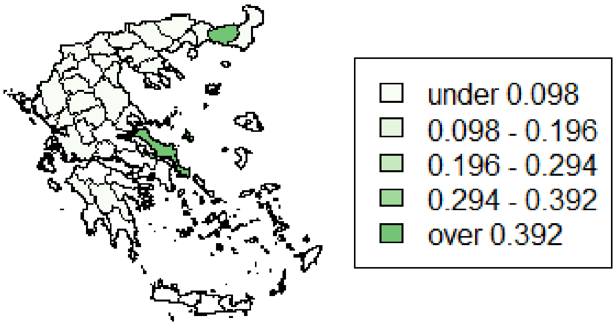
*g*


under 0.04
0.04 - 0.081
0.081 - 0.121
0.121 - 0.161
over 0.161

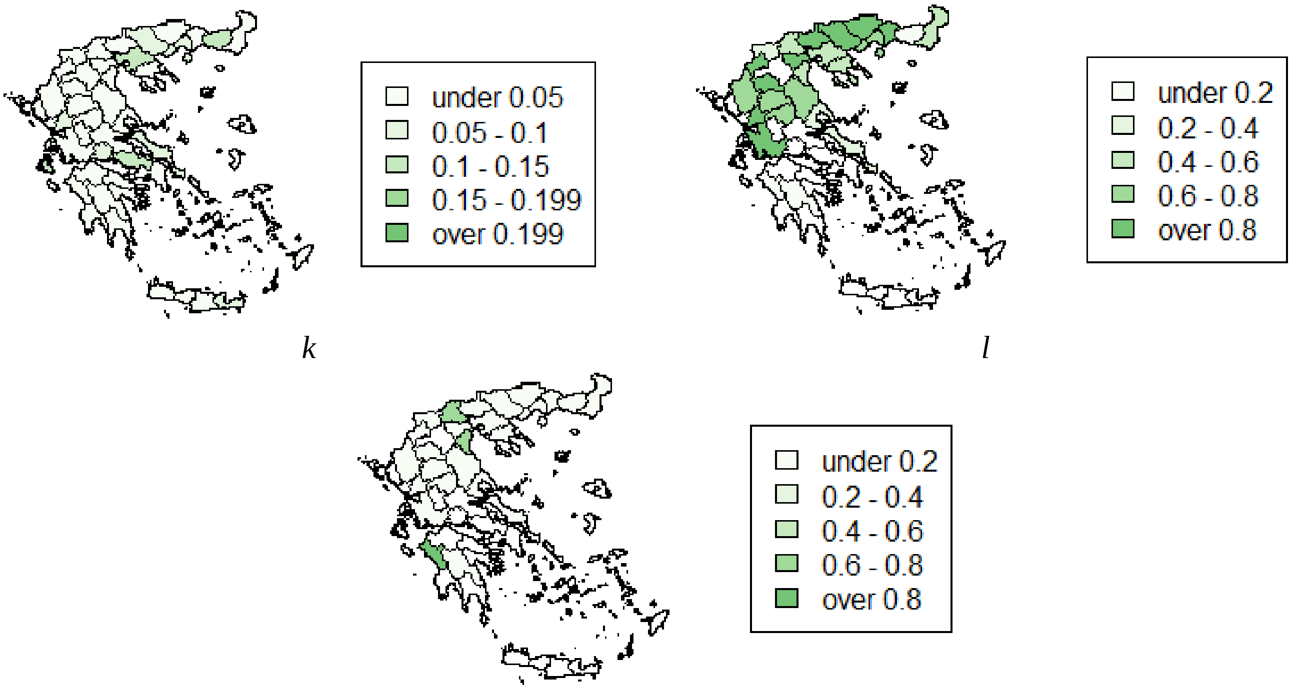
*h*


under 0.05
0.05 - 0.1
0.1 - 0.15
0.15 - 0.201
over 0.201

*i*


under 0.098
0.098 - 0.196
0.196 - 0.294
0.294 - 0.392
over 0.392

*j*



*k* *l*

*m*

**Figure 6:** Frequency of occurrence of renewable energy networks per alternative: a) A1, b) A2, c) A3), d) A4, e) A5,f) A6, g) A7, h) A8, i) A9, j) A10, k) A11, l) A12 and m) A13

## 5. Discussion

For the modeling of the renewable energy map of a country like Greece with so many potentials in renewable energy production from multiple sources (wind, hydro, solar and biomass), an analysis that may take multiple often uncorrelated data into account is needed. In this analysis, a 0-1 Weighted Goal Programming model is employed for the construction of the renewable energy map of Greece. This approach provides the decision maker with the advantage of weighting different goals that must be achieved given a specific weight to the corresponding slack variable (depending on the inequality of the constraint of the goal). Furthermore, additional constraints can be employed in order to make the approach more realistic to the examined problem. Often one of the major drawbacks of the proposed approach is that it is quite hard to get an expert or a panel of experts to provide weights to the examined criteria. In order to overcome this obstacle, all possible combinations ($n!$) have been examined providing equal number of solutions and on a second stage, disposability and Super-Efficiency DEA techniques have been employed in order to evaluate the ranges of each weights that are assigned to each criterion and to highlight the best solutions out of all the possible. Each weight's importance is categorized as Low ($L$), Medium ($M$) or High ($H$), based on a range of values, an incremental step ($m$) is introduced in order to provide better representation of the weights, leading to $m \cdot (n!)$ solutions. Results of disposability DEA model suggested that the most efficient solutions are the ones with higher weights in social acceptance criterion whereas the Super-Efficiency DEA model confirmed the above finding. The inputs and outputs of the DEA analyses (Disposability and Super-Efficiency) are the deviational variables derived from weight combinations. The procedure is graphically illustrated in Figure 7.

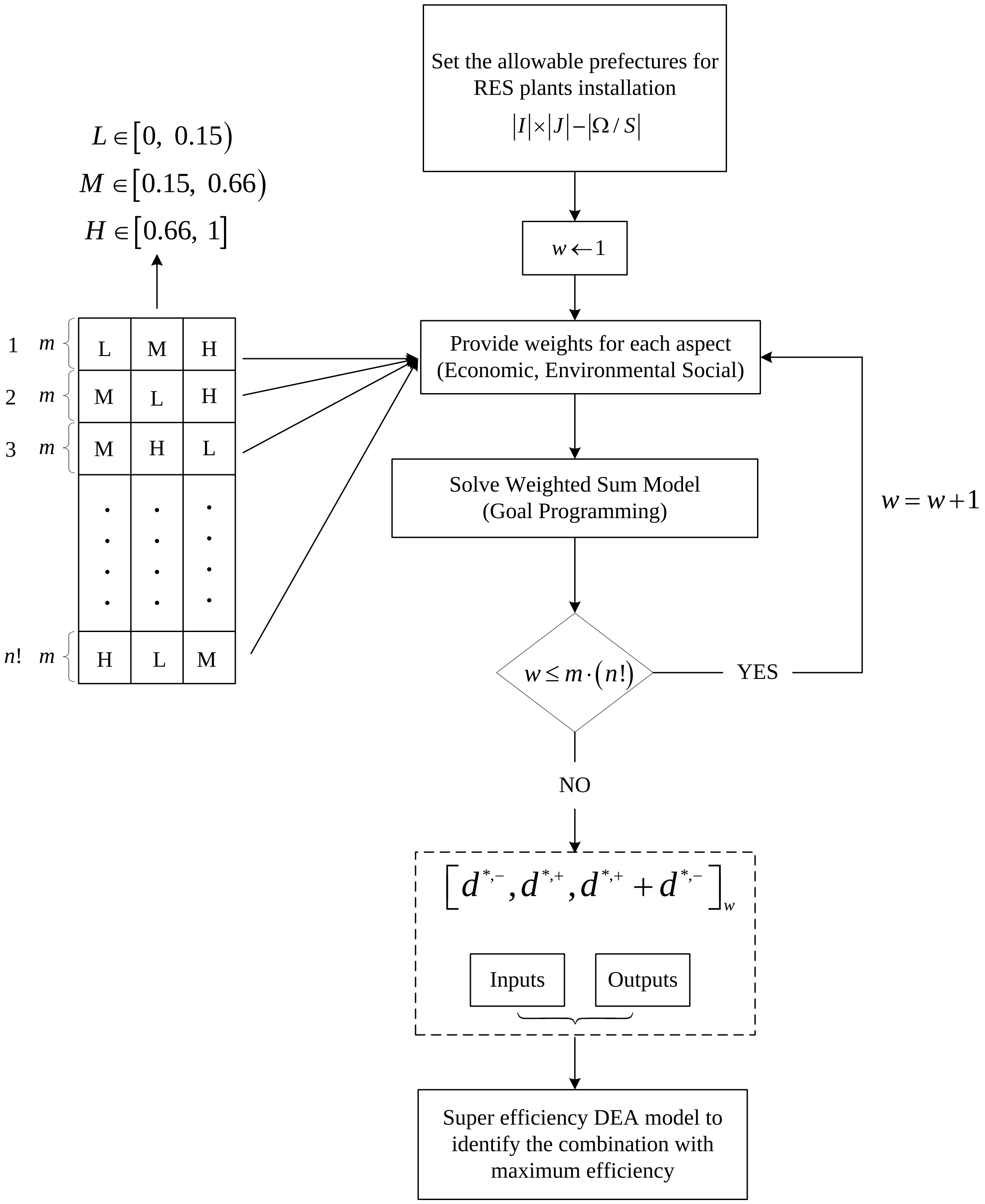


**Figure 7:** Graphical representation of the proposed approach.

## 5. Conclusions

The need to produce cleaner forms of energy is of great importance not only on environmental level, but on economic or social level as well. The links of this chain are generally intra-connected but may sometimes move towards different and conflicting directions, yet the right modeling framework should be provided in order to explore all the possibilities and investigate all the possible scenarios. The economic dimension in the installation of a renewable energy plant derives from the fact that this new forms of energy may indirectly reduce cost, because of the country's compliance with international environmental laws or directives, nevertheless, the transition to this new energy production form will directly increase the cost due to the expensive new technology. Regarding the social aspect, in many cases the adoption of new renewable energy technologies in a specific region causes the reaction of local communities or NGO's due to the non-existence of technical reports.

Taking all the aforementioned factors into account in this work, a 0-1 weighted goal programming model has been proposed setting goals regarding all the aspects that should be taken into account, namely economic, environmental and social. The economic pylon of the study encompasses the power production, the investment, the operation and maintenance cost and operating hours. The environmental pylon takes into account the equivalent tonnes of $CO_2$ avoided per annum after the installation of a specific renewable energy power plant and finally in the social pylon the jobs created, the unemployment and GDP of a prefecture have been taken into account. Due to the absence of a Decision Maker that would provide the relative importance to the variables associated with the goals of the study a full investigation of the solutions has been performed by changing the importance towards the three aforementioned criteria. Data Envelopment Analysis (DEA) has been used as a meta-analysis filter as the Pareto frontier is constructed showing all the non-inferior solutions. Treating each solution as a potential Decision Making Unit (DMU), and applying in order to keep the solutions with higher efficiency, an analysis of how weights affect the solutions and in which way is performed. Two DEA technologies have been chosen in this work; a classical output oriented DEA model where the undesirable output namely unemployment, is integrated into the model as the reciprocal, and DEA with disposability, where outputs are divided into desirable and undesirable. The results have shown that in the majority of efficient solutions based on disposability DEA technique, the highest values of weights have been assigned with 35% percentage to economic and environmental criterion whereas only the 25% of the cases high values have been assigned to the social criterion. Through the weak and strong disposability model it can be seen that the most efficient solutions are derived when high values are assigned to the social criterion, medium values are assigned to the environmental criterion and low values to the economic criterion. The results are confirmed from Super-Efficiency model as only two out of 600 possible combinations that were efficient using the weak and strong disposability model as well, gathered the highest efficiency. Furthermore, a frequency analysis has been performed for the all weights representations calculating the probability of occurrence of each plant at each prefecture. The networks provided have been designed based on previous works and techno-economic analyses excluding specific potential combinations of prefectures and renewable energy plants, thus the model takes into account not only the data provided from the aspect of the plants but are customized to the needs of Greece.

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## Appendix - Nomenclature

### Index

$i \in I$ renewable energy plant

$j \in J$ prefecture

$\Omega$ all possible combinations (Alternatives and Prefectures)

$S$ selected Alternatives and Prefectures

### Binary variables

$X_{ij}$ 1 if renewable plant $i$ will be installed in prefecture $j$, 0 otherwise

### Nonnegative variables

$d_{PP}^{+}$ over achievement of the Power Production goal

$d_{PP}^{-}$ under achievement of the Power Production goal

$d_{CO2}^{+}$ over achievement of the $CO_2$ goal

$d_{CO2}^{-}$ under achievement of the $CO_2$ goal

$d_{INV}^{+}$ over achievement of the Investment Ratio goal

$d_{INV}^{-}$ under achievement of the Investment Ratio goal

$d_{OM}^{+}$ over achievement of the Operations & Maintenance Cost goal

$d_{OM}^{-}$ under achievement of the Operations & Maintenance Cost goal

$d_{OH}^{+}$ over achievement of the Operating Hours goal

$d_{OH}^{-}$ under achievement of the Operating Hours goal

$d_{JOB}^{+}$ over achievement of the Job goal

$d_{JOB}^{-}$ under achievement of the Job goal

${}^{UMP}d_{j}^{+}$ over achievement of the Unemployment goal for each prefecture $j$

${}^{UMP}d_{j}^{-}$ under achievement of the Unemployment goal for each prefecture $j$

${}^{GDP}d_{j}^{+}$ over achievement of the GDP goal for each prefecture $j$

${}^{GDP}d_j^-$ under achievement of the GDP for each prefecture $j$

**Parameters**

$PP_i$ power produced by renewable plant $i$

$CO2_i$ tonnes of $CO_2$ avoided of renewable plant $i$

$INV_i$ Investment Ratio for renewable plant $i$

$OM_i$ Operations and Maintenance cost for renewable plant $i$

$OH_i$ Operating Hours for renewable plant $i$

$JOB_i$ Jobs created by installation of renewable plant $i$

$UMP_j$ Unemployment percentage at prefecture $j$

$GDP_j$ GDP at prefecture $j$

$G^{PP}$ Goal for Power Production

$G^{CO2}$ Goal for tones of $CO_2$ avoided

$G^{INV}$ Goal for Investment Ratio

$G^{OM}$ Goal for Operations and Maintenance

$G^{OH}$ Goal for Operating Hours

$G^{JOB}$ Goal for Jobs created

$G_j^{UMP}$ Goal for Unemployment percentage for prefecture $j$

$G_j^{GDP}$ Goal for GDP for prefecture $j$

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