MARMARA UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES
IN PURE AND APPLIED SCIENCES

COMPARISON OF LIFE CYCLE ASSESSMENT OF ELECTRICITY PRODUCTION MIX IN TURKEY WITH FUTURE ELECTRICITY PRODUCTION SCENARIOS

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Ph.D. THESIS

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Gülşah YILAN, a Doctor of Philosophy student of Marmara University Institute for Graduate Studies in Pure and Applied Sciences, defended her thesis entitled "Comparison of Life Cycle Assessment of Electricity Production Mix in Turkey with Future Electricity Production Scenarios", on June 4, 2018 and has been found to be satisfactory by the jury members.

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May, 2018 **Gülşah YILAN**

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TÜRKİYE’NİN ELEKTRİK ÜRETİMİ KARIŞIMININ YAŞAM DÖNGÜSÜ DEĞERLENDİRMESİNİN GELECEKTEKİ ELEKTRİK ÜRETİM SENARYOLARIYLA KIYASLANMASI

Fosil yakıtlardan kaynaklanan çevresel etkiler, iklim değişikliği problemlerinin ortaya çıkmasıyla birlikte, son yıllarda dikkat çekmeye başlamıştır. Sonuç olarak, sürdürülebilirlik kavramı, gelecek enerji yönetim politikalarının belirlenmesinde önemli bir başlık haline gelmiştir. 2016 yılı elektrik üretimi karışımında hala fosil yakıtlar önemli bir yer tutsa da, çevreyle ilgili farkındalık arttıkça Türkiye’deki yenilenebilir enerji kaynaklarının payları da artma eğilimindedir. Bu tezin amacı hem güncel durum hem de gelecek senaryoları için yaşam döngü değerlendirmesi (life cycle assessment) ile Türkiye’de elektrik üretimi aktiviteleriyle alakalı çevresel etkileri incelemektir. Ayrıca, bu tez başlıca elektrik üretim teknolojilerinin çok değişkenli karar analizi (multi criteria decision analysis) yöntemi ile daha kapsamlı bir şekilde incelenebilmesi için sürdürülebilirlik analizi yapmayı da amaçlamaktadır. Elektrik üretim alternatiflerinin farklı bakış açılarından ayrıntılı bir incelemesi yapıldıktan sonra, gelecekteki enerji planlama eylemleri için sürdürülebilir kalkınma politikaları sunulmuştur. Yaşam döngü değerlendirmesi sonuçları fosil yakıtlara dayalı senaryoların gelecek öngörülerinde artan çevresel zararlara sebep olduğunu, şimdiki seviyelerin ancak yenilenebilir teknolojilerin üretimdeki paylarının artması durumunda sabit tutulabileceğini belirtmektedir. Çok değişkenli karar analizi sonuçları yenilenebilir kaynakların fosil yakıt teknolojilerine kıyasla sürdürülebilirlik açısından en iyi seçenekler olduğunu ortaya koymaktadır. Her iki yöntemin sonuçları da sürdürülebilir gelecek hedeflerine ulaşmak için yenilenebilir teknolojilerin yürürlüğe koyulması gerektiği konusunda uyum göstermektedir.

ABSTRACT

COMPARISON OF LIFE CYCLE ASSESSMENT OF ELECTRICITY PRODUCTION MIX IN TURKEY WITH FUTURE ELECTRICITY PRODUCTION SCENARIOS

Fossil fuel related environmental impacts draw attention to emerging climate change mitigation problems for the last decades. As a consequence, sustainability concept is becoming a very important topic in policy making studies for future energy management. Although electricity generation mix in 2016 is still dominated by fossil fuels, shares of renewable energy sources tend to rise in Turkey as the awareness about the environment increases. The aim of this thesis is to investigate the environmental impacts related to electricity production activities in Turkey via life cycle assessment for current situation and also for future scenarios. Also, this thesis aims to employ sustainability analysis for further investigation of main electricity production technologies via multi criteria decision analysis. After a throughout investigation of electricity generation alternatives from different perspectives, sustainable development policies are offered for the future energy planning actions. Life cycle assessment results indicate that fossil fuel based scenarios cause increasing environmental burdens for future projections while current levels can only be sustained if renewable technologies have greater shares. Multi criteria decision analysis results reveal that renewables are the best options from sustainable point of view compared to fossil fuel technologies. Both methodology results mostly agree that renewable technologies should be put into practice for achieving sustainable future goals.

CLAIM FOR ORIGINALITY

Electricity generation activities from fossil fuels are the main contributor to climate change problems. For this reason, especially for the countries that rely on fossil fuels to supply their electricity demand, impacts associated with electricity generation activities should be carefully analysed. Up to recent past, only financial issues have been considered for the evaluation of generation alternatives. Yet, as the sustainability concept emerges with the rising environmental awareness, policy making strategies has changed in a way to consider all related issues like technical, environmental, and socio-economic factors. Among these factors, environmental issues are one of the least studied one compared to financial and technical aspects. In order to investigate the environmental impacts related with electricity sector in Turkey, a life cycle assessment methodology is applied for the 2014 electricity generation mix and also three possible future scenarios are computed for 2023 and 2030. Also, in order to draw a conclusion with respect to different preferences, multi criteria decision analysis strategy is applied for the year 2014.

To the best of our knowledge, this is the first study that comprehensively investigates electricity generation alternatives in Turkey with future scenarios via life cycle assessment. Not only available generation technologies, but also promising renewable alternatives are investigated. A very detailed inventory of Turkish electricity sector is introduced to the constructed model which can serve as a reference point to all electricity related studies from now on. On the other hand, this study is supported with multi criteria decision analysis method to assist policy makers to evaluate all of the related aspects in addition to financial issues. As far as we know, this is the first multi criteria decision analysis study combined with life cycle assessment results with the latest Turkey specific data.

May, 2018 **Gökçen A. ÇİFTÇİOĞLU** **Gülşah YILAN**

SYMBOLS

1,4-DB : 1,4 dichlorobenzene
Bq : Becquerel
C_2H_4 : Ethene
CFC : Chlorofluorocarbon
CFC-11 : Trichlorofluoromethane (Chlorofluorocarbon)
CH_4 : Methane
CO_2 : Carbon dioxide
CO_2-eq : Carbon dioxide equivalent
Fe : Iron
HCFC : Hydrochlorofluorocarbon
HFC : Hydrofluorocarbon
N : Nitrogen
N_2O : Nitrous Oxide
NMVOC : Non-methane volatile organic compounds
P : Phosphor
PFC : Perfluorocarbon
PM10 : Particulate matter with a diameter of less than 10 μm
PO_4^{3-} : Phosphate
Sb : Antimony
SF_6 : Sulphur hexafluoride
SO_2 : Sulphur dioxide
U235 : Uranium 235

ABBREVIATIONS

AHP : Analytic Hierarchy Process
BAU : Business-As-Usual
BNEF : Bloomberg New Energy Finance
BO : Build-Operate
BOT : Build – Operate – Transfer
BSR : Balancing and Settlement Regulation
CCGT : Combined cycle gas turbine
CED : Cumulative Energy Demand
CExD : Cumulative Exergy Demand
CST : Conventional steam turbine
DALYs : Disability Adjusted Life Years
EMRA : Energy Market Regulatory Authority
(Enerji Piyasası Düzenleme Kurumu, EPDK)
ENSAD : Energy-related Severe Accident Database
ENTSO-E : European Network of Transmission System Operators
EUAS : Electricity Generation Company
(Elektrik Üretim Anonim Şirketi, EÜAŞ)
EXIST : Energy Exchange Istanbul
(Enerji Piyasaları İşletme Anonim Şirketi, EPİAŞ)
GHG : Greenhouse Gas
GPt : Gigapoint
GWh : Gigawatt hour
GWP : Global Warming Potential
H : Hierarchist
IA : Impact Assessment
ILO : International Labour Office
IPCC : Intergovernmental Panel on Climate Change
ISO : International Organization for Standardization
kBq : Kilobecquerel
kWh : Kilowatt hour

LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCOE	Levelized Cost of Electricity
LNG	Liquefied Natural Gas
MAUT	Multi Attribute Utility Theory
MAVT	Multi-Attribute Value Theory
MCDA	Multi Criteria Decision Analysis
MCDM	Multi Criteria Decision Making
MENR	Ministry of Energy and Natural Resources (Enerji ve Tabii Kaynaklar Bakanlığı, ETKB)
OECD	Organization for Economic Cooperation and Development
OP	Official Plans
PPP	Public Private Partnership
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluations
PV	Photovoltaic
RDP	Renewables Development Pathway
R-O-R	Run-of-river hydropower
TETC	Turkey Electricity Transmission Company (Türkiye Elektrik İletim Anonim Şirketi, TEİAŞ)
TKI	Turkish Coal Enterprises (Türkiye Kömür İşletmeleri, TKİ)
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TOR	Transfer of Operation Rights
TP	Turkish Petroleum (Türkiye Petrolleri Anonim Ortaklığı, TPAO)
TPC	Transition Period Contracts
TSI	Turkish Statistical Institute (Türkiye İstatistik Kurumu, TÜİK)
TWh	Terawatt hour
UDHB	Transport, Maritime Affairs and Communications (Ulaştırma, Denizcilik ve Haberleşme Bakanlığı, UDHB)
WSM	Weighted Sum Method
WWF	World Widelife Fund (The World Wide Fund for Nature)

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1 INTRODUCTION

Electricity generation is one of the most important issues due to various reasons some of which may be listed as: (1) fossil fuels have limited reserves; (2) power generation sector has the biggest contribution to the environmental problems; (3) imported fuel dependency problem of countries result in supply security issues. The concern of this thesis is to conduct a throughout investigation of electricity generation alternatives from different perspectives and offer sustainable development policies for the future energy planning actions.

In Section 1.1, the aim of the study is stated with the introduction of the research idea. In Section 1.2, the problem investigated in the study is defined and a solution approach is proposed via Life Cycle Assessment (LCA) methodologies and Multi Criteria Decision Analysis (MCDA). In Section 1.3, a detailed background is given about the policy applications for Turkey between the years 1984 – 2016. In Section 1.4, a comprehensive literature survey is presented with the studies specific to Turkey.

1.1 Aim of the Study

Fossil fuel related environmental impacts draw attention to emerging climate change mitigation problems for the last decades. As a consequence of debates in the United Nations Conference on Climate Change (COP 21, Paris, 2015), about 200 countries, including Turkey, have adopted the ground breaking Paris Agreement to take measures against climate change mitigation by reducing fossil fuel consumption. The implementation of this agreement would decrease fossil fuel consumption rate and related consequences while enhancing renewable energy production technologies.

Since United Nation (UN) General Assembly unanimously declare the decade 2014–2024 as the “decade of sustainable energy for all”, namely to “ensure access to affordable, reliable, sustainable and modern energy for all”, it is inevitable for countries to shift renewable technologies from fossil related counterparts, at all (UNGA, 2014).

The sustainability assessment, which is an essential topic in energy production technologies, is defined as “a tool that can help decision-makers and policymakers decide which actions they should or should not take in an attempt to make society more sustainable" (Ness et al., 2007).

The LCA part of this study aims to indicate the environmental impacts owing to electricity generation in Turkey for year 2014 and also estimate the course of change in the impacts with future projections for 2023 and 2030. In order to calculate the environmental impacts LCA methodology is used with different levels of indicators. Both single issue and multiple issue (midpoint and endpoint) indicators are computed in this study. Single issue methods used are Intergovernmental Panel on Climate Change (IPCC) 2013 methodology (Stocker, 2013, Santos et al., 2014), Cumulative Energy Demand (CED) method (Frischknecht et al., 2007), and Cumulative Exergy Demand (CExD) method (Frischknecht et al., 2005). Problem oriented (midpoint) impact assessment methods used are CML 2 baseline 2000 method (Guinée et al., 2002) and ReCiPe (H) method with hierarchist perspective (Goedkoop et al., 2009). Additionally, ReCiPe (H) endpoint method is employed. The combined results are to be offered to decision making authorities to constitute a scientific basis for sustainable future energy policies.

The MCDA part of the study aims to rank the main electricity generation technologies for Turkey according to their performance scores. In this study, four criteria groups, which are economic, technical, environmental, and socio-economic, are defined in parallel with sustainable development concept. Then, a number of twelve sustainability indicators are selected from literature. The indicator selection is based on their suitability under the main evaluation criteria. MCDA methodology is employed with a weighted sum multi-attribute utility theory (MAUT) approach for different sensitivity cases.

In short, the aim of this thesis is to investigate the environmental impacts related to electricity production activities via LCA for current situation and also for future scenarios. Also, this thesis aims to employ sustainability analysis for further investigation of main electricity production technologies. Sustainability analysis is conducted from financial, technical, environmental, and social point of views via MCDA.

1.2 Problem Definition and Solution Approach

Although electricity generation mix in 2016 is still dominated by fossil fuels with a total share of 67%, shares of renewable energy sources tend to increase during the last decade in Turkey as sustainability concept emerges with increasing awareness about the environment (TETC, 2014). In the Institute for Energy Economics and Financial Analysis (IEEFA, 2016) report, authors propose a future scenario for Turkey with diversifying its energy mix by adding larger amounts of renewable - wind and solar- resources to keep away from fossil fuels. Since national consensus clearly favours better energy security and greater diversification in how the country fuels its electricity grid, renewable energy has the potential to provide greater benefits and a better economic alternative for Turkey on its path to becoming a more competitive economy.

There are various studies in the literature concerning with the sustainability of electricity generation technologies. Incekara and Ogulata (2017) emphasize the need for energy policies in reduction on emissions of greenhouse gases, minimization of the use of power plants that use fossil fuels that have significant impacts on ecosystem, environment and causes of climate change. Also, Balat (2010) mentions that the fossil fuel dependency problem of Turkey may be solved via diversification of the electricity generation mix from a sustainable point of view. Reducing the share of fossil fuels in the electricity mix would not only reduce the environmental impacts, but also the costs, injuries and fatalities, while also improving energy security problem (Atilgan and Azapagic, 2017, Ozcan, 2018).

In order to propose a better future scenario, current situation and all possible circumstances should be carefully analysed. The most widely used approaches to the modelling of the energy systems have been life cycle assessment (LCA), cost benefit analysis (CBA) and multi criteria decision analysis (MCDA) (Kumar et al., 2017).

LCA is an analytical tool that investigates the total environmental impacts of a product, process or human activity including raw material acquisition, production and use, and waste management. In other words, LCA is a process to analyse and assess the environmental impacts of a product, process or activity over its whole lifecycle. This comprehensive character makes LCA an essential environmental management tool that identifies and quantifies energy and materials used and wastes released to the environment and assesses the impact of those inputs and outputs searching for environmental improvements. As in all complex assessment tools, LCA has some limitations and strengths which are discussed in the previously published studies (Curran, 2013, Strantzali and Aravossis, 2016).

Life cycle impact assessment (LCIA) methods are mainly classified in two groups as single issue and multiple issue methods. Single issue methods consider one indicator while multiple issue methods, which are divided into two groups as midpoint and endpoint methods, handle a combination of complex indicators.

Single issue methods, such as Carbon Footprint, are certainly more attractive than LCA due to their simplicity, but they may cause oversimplification. Studies on electricity generation technologies confirm that focusing only on one indicator may lead to wrong conclusions concerning their environmental consequences. Actually, many renewable energy technologies do have an impact on water, ground, wildlife, landscape; therefore the evaluation of CO_2 emissions results is limited. Thus, a range of key indicators must be considered to evaluate the sustainability of energy generation technologies and a LCA approach is desirable to avoid impact shifting from one lifecycle phase to another. In this regard, also the utilization of a Life Cycle Sustainability Assessment (LCSA) model is considered a valid supporting tool (Asdrubali et al., 2015).

Multi criteria decision making (MCDM) techniques are popular in sustainable energy management. These techniques provide solutions to the problems involving multiple objectives about energy policy and management implications. The objectives are generally conflicting and so, the solution mainly depends on the preferences of the decision-maker. This tool is becoming popular in the field of energy planning due to the flexibility it provides to the policy-makers to take decisions while considering all the criteria and objectives simultaneously (Troldborg et al., 2014, Strantzali and Aravossis, 2016, Kumar et al., 2017).

Decision-making in environmental projects requires consideration of different aspects including socio-political, environmental, and economic impacts and is often complicated by various stakeholder views. MCDA is used as a formal methodology to handle available technical information and stakeholder values to support decisions in many fields and can be especially valuable in environmental decision making. Various

MCDA methods have been successfully used for environmental applications. A previous paper suggests that even though the use of the specific methods and tools vary in different application areas and geographic regions, recommended course of action does not vary significantly with the method applied (Huang et al., 2011).

MCDA methods utilized in energy planning processes are considered as the most suitable methods of solving issues related to energy. No single MCDM model can be ranked as the best or worst. Every method has its own strength and weakness depending upon its application in all the consequence and objectives of planning. Mainly, three types of MCDM models exist; namely Value Measurement Models; Goal, Aspiration and Reference Level Models; and Outranking Models. An application of value measurement or utility based models MAUT is among the mostly preferred methods for ranking energy technologies. MAUT is the easiest method for value normalization and also it allows performing different sensitivity case applications from an objective point of view. The weaknesses and strengths of MAUT method are discussed in the previously published study (Kumar et al., 2017). The main strength of this method is that it allows simultaneous computation of preference order for all selected generation alternatives. Yet, the weakness of the method is the uncertainty about the outcome of the decision criteria.

1.3 Background of Turkish Electricity Sector Policy Implications

In the beginning of 1990s, Turkish Electricity Market has undergone a major restructuring process. In 2000s, the market reaches stability with the announcement of the Electricity Market Law. This restructuring process is based on two main pillars; liberalization of the market and privatization of the public assets. Some of the major steps taken in this process are covered as given below (EUAS, 2011).

1984: Law No. 3096 on the Granting Authorization to Institutions other than the Turkish Electricity Authority for the Generation. Transmission, Distribution and Trade of Electricity enables private sector to engage in electricity generation, distribution, and trade. This law also establishes a legal basis for electricity generating plants (except nuclear) to be built and operated with the Build – Operate – Transfer (BOT) model and to be operated with the Transfer of Operation Rights (TOR) model.

1994: Law No. 3996 on the Realization of Certain Investments Services in the BOT Model forms the legal basis for numerous categories of infrastructure investments to be built under this model. The infrastructures include transportation, energy and water supply and treatment investments.

1997: Law No. 4283 on the Establishment and Operation of Electricity Generation Plants and Energy Sales under the Build-Operate (BO) Model forms the legal basis for only thermal power plants. With this regulation, Public Private Partnership (PPP) projects are implemented for the first time in Turkey and a number of electricity production projects have been realized as BOT and later as BO projects.

2001: Electricity Market Law No. 4628 sets the basis a financially sound and transparent electricity market development. The market is operating in a competitive environment under civil law provisions. The goal of the law is to deliver sufficient, good quality, low cost and environment friendly electricity to consumers. Also, the aim is to provide the autonomous regulation and supervision of the market. After the implementation of this law, Energy Market Regulatory Authority (EMRA)[1] is established. Private initiatives are allowed to participate in the market after a licensing scheme is introduced. Natural Gas Market Law No. 4646 mentions that BOTAŞ Petroleum Pipeline Corporation[2] has the ownership of the existing transmission lines. This law also allows private companies to construct new transmission lines. Besides, the third party access to the transmission lines operated by BOTAŞ is decided to be made through regulated tariffs.

2003: The Communiqué on Procedures and Principles Concerning Financial Settlement in the Electricity Market (“Communiqué”) is applied. The financial settlement applications under the Communiqué form the first step of the efforts in establishing the electricity market. Petroleum Market Law No. 5015 indicates that the prices in the petroleum trade are formed according to the nearest accessible world liberal market conditions.

2004: “Strategy Papers” are launched with the laws and regulations issued which are supported by High Planning Council Decisions. The theme of the 1st Strategy Paper is

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[1] Enerji Piyasası Düzenleme Kurumu (EPDK)

[2] Boru Hatları ile Petrol Taşıma Anonim Şirketi (BOTAŞ)

"Electricity Sector Reform and Privatizations". A detailed plan for privatization of electricity distribution and generation assets is set forth with this strategy paper. The existing Turkish Power System Electricity Market Grid Regulation and System Security and Quality of Supply (Electricity Transmission System Supply Reliability and Quality Regulation) regulations have been in force since 2003 and 2004, respectively.

2005: Renewable Energy Law No. 5346 is issued to incentivize the usage of renewable sources in power generation. A temporary balancing and settlement mechanism is established to help transmission system operator Turkey Electricity Transmission Company (TETC)[3] with its real-time task of balancing demand for and supply of electricity.

2006: A modern day-ahead market with hourly prices is established and the first Organized Electricity Market starts to operate with Balancing Mechanism only. As soon as it is established, this mechanism generates market based prices for electricity and it is seen as an opportunity for attracting merchant power producers to invest in this growing and promising market (Balancing and Settlement Regulation (BSR)). Transition Period Contracts (TPCs) are signed (Worldbank, 2015).

2007: Energy Efficiency Law No. 5627 aims to increase efficiency in using energy sources via using energy effectively, avoiding waste, decreasing the burden of energy costs on the economy and protecting the environment. Geothermal Resources and Natural Mineral Water Law No. 5686 regulates the exploration, ownership rights, economic use of the resources and development. Nuclear Energy Law No. 5654 regulates the construction and operation of nuclear power plants according to the energy plans and policies.

2008: Law No. 5784 on Amendments on Electricity Market revises Law No. 4628 in terms of integration of interconnected system, auto-producer electricity generation amount limits, wind power plant construction conditions, and supply security issues. Also, new BSR draft is proposed; privatization of distribution companies (DisCo) is restarted; ancillary services are regulated and automatic pricing mechanism is established.

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[3] Türkiye Elektrik İletim Anonim Şirketi (TEİAŞ)

2009: BSR is finalized. The First Stage of Organized Electricity Market including Day Ahead Planning, Balancing Power Market and Hourly Settlement is introduced. "Supply Security and Supply Diversification" theme is published as the Second Strategy Paper.

2010: Electricity Generation Company (EUAS)[4] privatization process is initiated in order to fully privatize the assets. The privatization does not include the large hydropower plants which have strategic importance. As the first step to integrate Turkish electricity grid with Europe, the European Network of Transmission System Operators (ENTSO-E) test connection is initiated.

2011: The Second Stage of Organized Electricity Market is started; Day Ahead Market and Collaterals Mechanism set off. Renewable Law is revised and feed-in tariff is categorized for different type of sources. Also, local equipment bonus is introduced. Renewable investments except hydropower have become more attractive with the introduced improvements.

2012: Privatization process of EUAS is completed. The transition period contracts signed in 2006 are terminated.

2013: New Electricity Market Law No. 6446 is declared with the aim to increase reliability and transparency of the market. Distribution companies are fully privatized by the end of the transition period. The distribution and retail activities are unbundled. The New Turkish Petroleum Law No. 6491 is established to provide that the petroleum resources of the Republic of Turkey are rapidly, continuously and effectively explored, developed and produced by preserving the national interests.

2014: Nuclear energy investments are launched. Private sector investments on energy market dominate over public sector.

2015: Energy Exchange Istanbul (EXIST)[5] is launched with an aim to plan, establish, develop and manage energy market within the market operation license in an effective, transparent, reliable manner. Intra Day Market started to operate to take a well-balanced and active responsibility of the participants of the Turkish Electricity Market. This market place further increases market sophistication and provides additional means for balancing especially for renewables.

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[4] Elektrik Üretim Anonim Şirketi (EÜAŞ)

[5] Enerji Piyasaları İşletme Anonim Şirketi (EPİAŞ)

2016: In order to support renewable energy investments and encourage local manufacturing of renewable generation assets New Investment Model for Renewables, Renewable Energy Resource Area[6] Mechanism, has been introduced. Turkey Electricity Trading and Contracting Company[7] has been enabled to make power acquirements from operational lignite power plants.

1.4 Literature Review

As mentioned before, a widely used tool for the modelling of the energy systems is LCA. Although there are a number of studies conducted for the calculation of environmental impacts of power generation (Santoyo-Castelazo et al., 2011, Georgakellos, 2012, Liang et al., 2013, Garcia et al., 2014, Asdrubali et al., 2015, Tomasini-Montenegro et al., 2017), studies concerning LCA applications to electricity generation technologies in Turkey are very limited. Some of the studies for Turkey are explained as follows. Gunkaya et al. (2016) investigate the environmental performance of electricity generation options with CML impact assessment methodology. Demir and Taşkın (2013) compare wind turbines in terms of environmental impacts, embodied energies and energy payback times. They use CML method for the calculation of environmental impacts. Atilgan and Azapagic (2015) estimate the life cycle environmental impacts of electricity generation from the fossil fuel power plants via CML 2001 impact assessment method. They also estimate the life cycle environmental impacts of electricity generation from the renewable power systems via the same method (Atilgan and Azapagic, 2016). Şengül et al. (2016) present a LCA of lignite from extraction to the delivery to the power plant with TRACI, CML, and ReCiPe impact assessment methods and they also present the potential degree of environmental improvements.

The other method employed is MCDA. The MCDM concept is drawing attention for energy strategy planners worldwide. As Mardani et al. mention in their extensive review, out of 40 countries or nationalities employed in decision making studies from 1995 to 2015 in various fields of energy management, Turkey is the first country in the ranking with the highest number of papers (Mardani et al., 2017). Also Marttunen et al.

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[6] Yenilenebilir Enerji Kaynak Alanı (YEKA)

[7] Türkiye Elektrik Ticaret ve Taahhüt Anonim Şirketi (TETAŞ)

(2017) mention that Turkey is one of the pioneer countries that publishes the most articles concerning MCDM during 2000-2015.

MCDA studies concerning national electricity grid and policy implications are numerous (Brand and Missaoui, 2014, Garcia et al., 2014, Maxim, 2014, Santos et al., 2014, Santoyo-Castelazo and Azapagic, 2014, Klein and Whalley, 2015, Štreimikienė et al., 2016, Heidari et al., 2017, Malkawi et al., 2017, Santos et al., 2017, Volkart et al., 2017); some of the papers conducted for Turkey are discussed below. Büyüközkan and Güleryüz (2017) use MCDA methodology with linguistic interval fuzzy preference relations in order to evaluate renewable energy resources. Özkale et al. (2017) employ Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) methodology in order to make suggestions regarding the energy resource that Turkey should depend on for investment, incentive, environmental, and economic policies for future energy planning with regard to the selected energy resource. Balin and Baraçli (2015) investigate renewable energy alternatives by using a fuzzy Analytic Hierarchy Process (AHP) procedure based upon type-2 fuzzy sets, and fuzzy multi-criteria decision-making based upon the interval type-2 Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method. Uyan (2017) employs MCDA method for determining the ideal locations for solar power plant via AHP. Yalcin and Gul (2017) investigate geothermal potential of selected areas via AHP as an application of MCDA methodology. Atilgan and Azapagic (2016) report sustainability analysis of future electricity generation options performed via Multi-Attribute Value Theory (MAVT).

2 MATERIAL AND METHOD

In the first part of the study, electricity generation alternatives are comprehensively investigated from environmental point of view via LCA methodology with current data and also future scenarios are computed for 2023 and 2030. Then, further investigation is conducted with MCDA methodology which is applied to draw a broad perspective of the electricity generation related costs of different generation technologies.

2.1 Life Cycle Assessment (LCA)

In sustainable energy decision making process, generally financial and technical aspects are of great importance while environmental factors are ignored. In order to investigate the environmental burdens of electricity generation technologies LCA methodology is applied. In International Organization for Standardization (ISO) 14040, LCA is defined as the “compilation and evaluation of the inputs, outputs and potential impacts of a product system throughout its life cycle” (ISO, 2006). Thus, LCA is a useful tool for exploring the possible environmental burdens of a product or service at all stages of their life cycle including the resource extraction, material production, use, recycle and disposal.

The environmental impacts associated with the electricity generated and supplied in Turkey are evaluated using a process-based LCA methodology following the ISO guidelines. According to the ISO 14040, LCA consists of four phases: (1) Goal and Scope Definition, (2) Inventory Analysis, (3) Impact Assessment, and (4) Interpretation (**Figure 2.1**) (UNEP, 2003).

The LCA has been carried out following the ISO 14040/14044 guidelines (ISO, 2006). SimaPro 8.2.0.0 PhD software package is used to estimate the environmental impacts per kWh and also used to calculate total environmental impacts for electricity generated in years 2014, 2023, and 2030.

2.1.1 Goal and scope definition

The goal of the study is to estimate the life cycle environmental impacts of electricity generated in Turkey for the years 2014, 2023, and 2030. 2014 is selected as the baseline year since it is the latest year verified data obtained before the computations of this thesis.

2.1.1.1 Functional unit

Functional unit is the basis for comparing the evaluated results of selected generation technologies. All of the environmental impacts are normalized and compared according to this value. The functional unit is selected as 1 kWh electricity generated from each technology for 2014. Also, the total electricity generated from available technologies for future scenarios are compared.

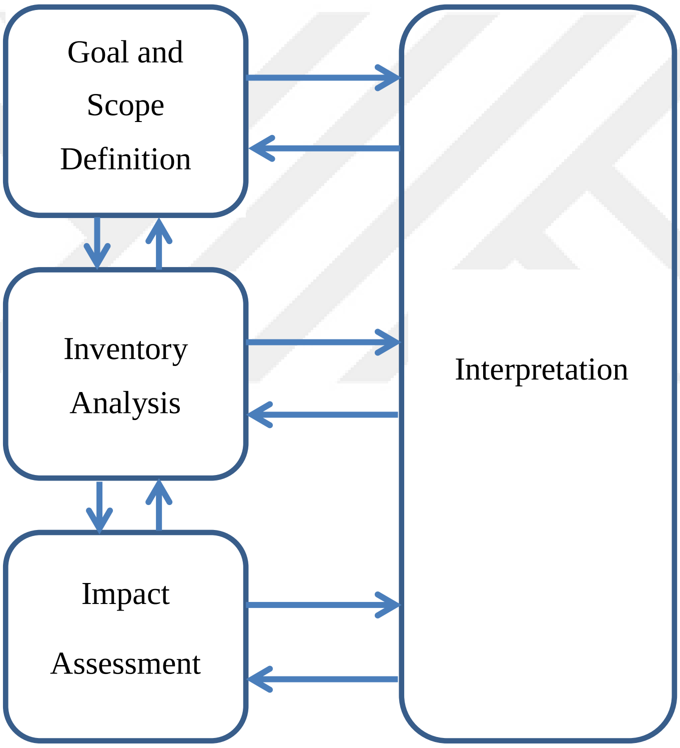

Figure 2.1 Life cycle assessment framework (UNEP, 2003)

2.1.1.2 System boundaries

The scope of this study is “cradle-to-gate” including extraction, processing and transport of fuels; operation of the power plants along with power plant construction. Since the functional units are related to the generation rather than supply of electricity, its distribution and consumption are out of the system boundary (**Figure 2.2**).

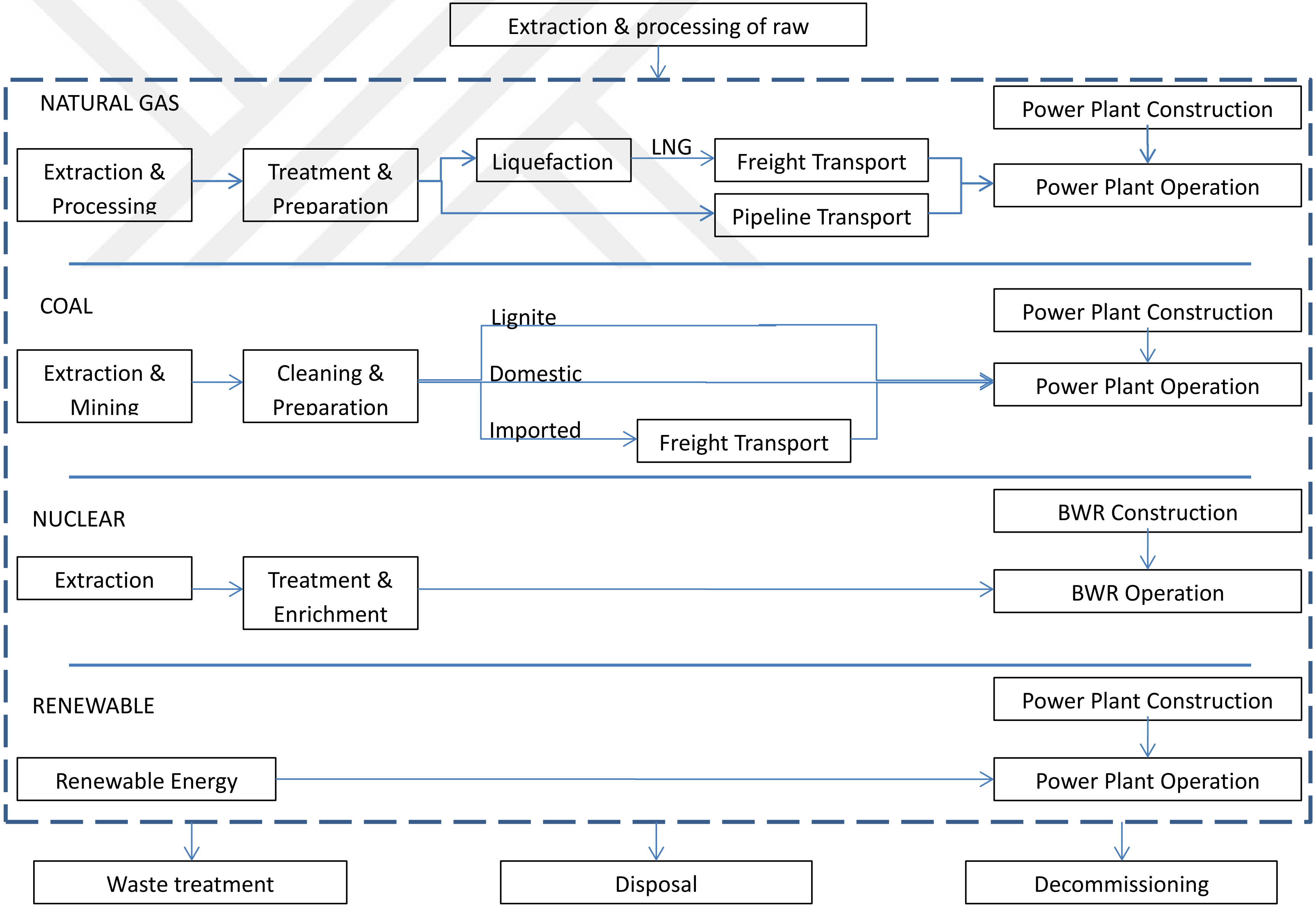

Figure 2.2 System boundaries of electricity generation technologies selected for LCA study

2.1.1.3 Assumptions and limitations

Assumptions made in LCA study are listed in Appendix A1.

2.1.2 Life cycle inventory (LCI) analysis

Life cycle inventory (LCI) analysis includes quantification of each proses related to the energy carriers and raw materials used, the emissions to atmosphere, water and soil, and different types of land use. Two different main perspectives on how to perform LCA exist: attributional and consequential modelling.

The attributional approach to LCI is employed to allocate or attribute, to each product being produced in the economy at a given point in time. This approach also serves to acquire the portions of the total pollution including resource consumption flows occurring from the economy. The consequential approach to LCI is used to estimate the changes in flows to and from the environment in case of different potential decisions (Curran et al., 2005).

The model used in this study is an example of attributional modelling since it examines the environmental impacts of the main electricity generation technologies and compares the impacts of these technologies with the same functional unit.

Once the model is determined, data collection part follows. There exist two types of data: foreground and background data. Foreground data refers to specific data needed to acquire for modelling the system. Generally, this data is used to describe a particular or a specialized production system. Background data is used for the production of generic materials, energy, transport and waste management.

Foreground data is essential for the credibility of modelling studies since it reflects the real system, but, it is not always possible to find these specific data sets. Instead, background data can be used from SimaPro databases and also from literature. For this study, the specific data based on regional official reports and statistics is used when accessible; however, the missing values are based on background data.

After data collection, process type is to be determined. Each process can be introduced into the computation program either as a unit or a system process. A unit process is a combination of the emissions and resource inputs from process steps including the inputs from other unit processes. A system process, however, is the inventory result of an overall LCA and it does not provide insights into the inputs and outputs of the separate supply chain processed in the production system. A system process is assumed as a black box.

In general, system processes are used in LCA screenings while unit processes are preferred in full LCAs (Mark Goedkoop, 2013). In this study, inventory processes are introduced to the computation program as unit processes.

2.1.2.1 Electricity generation technologies to be assessed

The schematic of electricity generation technologies in Turkey by the year 2014 are given in **Figure 2.3**. Background data is obtained from Ecoinvent v3.01 database (Wernet et al., 2016). Total electricity generated in 2014 is gathered from Turkish Electricity Transmission Company (TETC) statistics. Lignite and hard coal data is gathered from Turkish Statistical Institute (TSI)[8] and Turkish Coal Enterprises (TKI)[9]. Natural gas data is gathered from Turkish Petroleum (TP)[10]. Hydropower, wind and solar PV processes are based on the Ecoinvent database due to the lack of country-specific data.

Future scenarios for years 2023 and 2030 are based on the publication by World Wildlife Fund for Nature (WWF-Turkey) supported by European Climate Foundation and collaborated with Bloomberg New Energy Finance (BNEF) (WWF, 2014).

2.1.2.2 Fuel supply data analysis

Turkey’s electricity sector is dominated by fossil fuels despite its considerable renewable energy potential in solar, wind and hydro alternatives. Lignite is extracted from domestic sources and 89.10% of the extracted lignite is used for electricity production. Hard coal and natural gas requirements of the country are basically met by the imports resulting in a high level of import dependency and supply security problems. Total supplied fossil fuels and their electricity production shares are given in **Table 2.1**.

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[8] Türkiye İstatistik Kurumu (TÜİK)
[9] Türkiye Kömür İşletmeleri (TKİ)
[10] Türkiye Petrolleri Anonim Ortaklığı (TPAO)

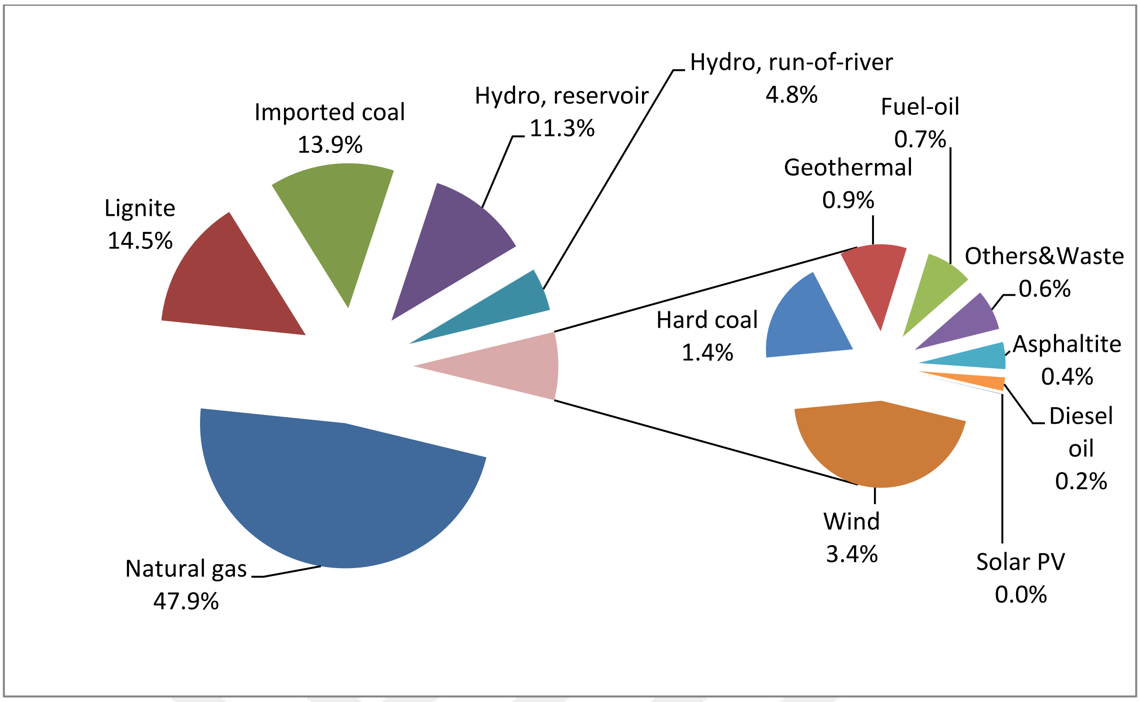

Figure 2.3 The distribution of electricity generation technologies in 2014 (TETC, 2014)

Table 2.1 Fuel supply inventory for 2014 (TP, 2015, TSI, 2016)

Source	Domestic	Imported	Total Supply, 2014	Electricity Production Share, %
Lignite	59.592 E+09 kg	-	59.592 E+09 kg	89.10%
Hard Coal	1.815 E+09 kg	27.015 E+09 kg	28.830 E+09 kg	43.90%
Natural Gas	0.500 E+09 m3	49.300 E+09 m^3	49.800 E+09 m^3	50.00%

2.1.2.3 Transport processes of imported fuels

In order to calculate the impacts of imported fuels, import distances are also required. Transport distances of fuels are obtained by online mapping. Pipeline distances are gathered from the reports published by Republic of Turkey Ministry of Energy and Natural Resources (MENR)[11] and Republic of Turkey Ministry of Transport, Maritime Affairs and Communications (UDHK)[12].In **Table 2.2**, hard coal imports are given with import shares and transport distances (TKI, 2015). For hard coal, imported fuel is assumed to be transported from port to port via tankers. In **Table 2.3**, total import shares of natural gas and their transport distances are given (TP, 2015). Natural gas is

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[11] Enerji ve Tabii Kaynaklar Bakanlığı (ETKB)
[12] Ulaştırma, Denizcilik ve Haberleşme Bakanlığı, UDHB

imported in two ways: via conventional pipeline transport and via tankers in liquefied natural gas (LNG) form. Pipeline transport is also constructed in two types: onshore and offshore.

Table 2.2 Hard coal import shares for 2014 and transport distances (TKI, 2015)

Imported Hard Coal	Share %	Transport, tkm
Colombia	31.6	10.74
Russian Federation	29.1	8.7
USA	14.5	9.5
South Africa	13.4	9.9
Ukraine	3.8	1.1
Australia	2.1	16.7
Canada	1.7	18.85
Others	3.8	N/A*

*N/A: not available

Table 2.3 Natural gas imports for 2014 and transport distances (TP, 2015)

Imported Natural Gas	Share %	Pipeline Transport, tkm		Sea Transport, tkm
		Onshore	Offshore	
Russian Federation				
Blue Stream	30	0.26	0.59	-
Western Route	26		4.64	-
Iran	19		2.27	-
Azerbaijan	9		1.48	-
Algeria (LNG)	9			1.78
Nigeria (LNG)	7			6.18

2.1.3 Life cycle impact assessment (LCIA)

The ISO 14040/44 standard states that a LCA is a comprehensive investigation of the inputs and outputs in addition to the environmental impacts of a product or service through its life cycle (ISO, 2006). According to this definition, impact assessment plays a vital part in a LCA study. LCIA is the phase in which the degree and significance of the environmental impacts of a product or service is interpreted and evaluated.

ISO 14040/44 differentiates between:

- *Obligatory elements*: classification and characterization.
- *Optional elements*: normalization, ranking, grouping and weighting.

This indicates that according to the ISO, a study must include classification and characterization, at least, so as to be considered as a LCA study.

There exist many impact assessment methods, including single issue methods, problem oriented (midpoint) methods and damage oriented (endpoint) methods. Single issue methods are specific calculation procedures focused on only one impact category like global warming potential, cumulative energy demand, and so on. The ISO standard defines the indicators between the inventory results (i.e. emission) and the "endpoints" as "midpoint level" indicators.

Usually, midpoint indicators have a lower uncertainty because they are close to the inventory results. Thus, most of the environmental mechanism is already modelled. On the other hand, endpoint indicators can have considerable uncertainties. Yet, decision makers can easily understand and interpret endpoint indicators compared to midpoint ones (Mark Goedkoop, 2013).

Both single issue and midpoint level indicators are computed in this study. Single issue methods used are IPCC 2013 methodology (Stocker, 2013), Cumulative Energy Demand (CED) method (Frischknecht et al., 2007), and Cumulative Exergy Demand (CExD) method (Frischknecht et al., 2005). Problem oriented (midpoint) impact assessment methods used are CML 2 baseline 2000 method (Guinée et al., 2002) and ReCiPe (H) method with hierarchist perspective (Goedkoop et al., 2009). Additionally, ReCiPe (H) endpoint method is employed. A detailed explanation of impact assessment methods are given in the following subsections.

2.1.3.1 Single issue methods

As mentioned before, single issue methods consider a limited series of input data and conclude only specific results according to the method chosen. Even these methods are relatively easy to use; many impacts are out of the scope and thus out of sight due to their limited perspective. Moreover, single issue methods are not in accordance with ISO 14044 because this standard states a comprehensive assessment of all relevant impact categories for the study. But single issue methods may leave out impact categories that have a significant impact. Thus, single issue methods should be supported with detailed midpoint or endpoint methods in order to draw a conclusion.

Single issue methods applied in this study are IPCC 2013 methodology (Stocker, 2013), Cumulative Energy Demand (CED) method (Frischknecht et al., 2007), and Cumulative Exergy Demand (CExD) method (Bösch et al., 2006).

- ✓ **IPCC 2013 methodology**

IPCC 2013 is a revision of the method IPCC 2007 previously developed by the International Panel on Climate Change for estimating the Global Warming Potential (GWP) of selected processes (Stocker, 2013). GWP is an indicator for comparisons of the global warming impacts of different gases. By definition, it is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2). Thus, GWP score indicates how much a given gas warms the Earth compared to CO_2 over that specific time period. The time period usually referred for GWPs is 100 years but 20 years may be used in some cases, too. GWP scores allow to build a common unit of measure giving analysts the possibility to calculate emissions estimates of different gases (for example, to compile a national Greenhouse Gas (GHG) inventory), and assist policy makers to compare emission reduction opportunities across gases and also sectors.

CO_2, by definition, has a GWP of 1 independent on the time period used since it is used as the reference. CO_2 stays in the climate system for a very long time and it is the main reason for the increase in atmospheric concentrations of CO_2 that may last thousands of years.

Methane (CH_4) is another GHG and estimated to have a GWP score about 28–36 over 100 years. CH_4 emissions last less than $CO_{2,}$ about a decade on average. But, CH_4 absorbs more energy than CO_2. Due to its shorter lifetime and higher energy absorption, it contributes to the GWP. The CH_4-based emissions also result in some indirect effects, for example CH_4 is a precursor to ozone, and ozone is itself a GHG.

Another GHG is nitrous oxide (N_2O) which has a GWP of 265–298 for a 100-year timescale. N_2O emissions stay in the atmosphere for more than 100 years, on average.

The other GWP sources are chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6). These are called high-GWP gases due to their capacity to trap substantially more heat than CO_2 for a given amount of mass (IPCC, 2007).

In this study, the IPCC 2013 methodology is used as a basis for estimating national inventories of anthropogenic emissions by sources and removals by sinks of greenhouse gases. A lifetime of 100 years is selected for GWP calculations.

✓ Cumulative energy demand (CED) method

Sustainable development policy making efforts mainly concern the reduction of energy consumption. Since many environmental problems like climate change are directly associated with the energy use, Cumulative Energy Demand (CED) is a very advantageous measure for making improvements. The method is also easy to comprehend for consumers, politicians or managers; all kinds of decision-makers. Thus, CED method is a useful tool for drawing a general perspective to the energy related environmental impacts in a life cycle and to make a comparison between different generation options.

The total energy use in a country is a remarkable benchmark to measure and control the success of policy strategies for reducing the energy use. Since diverging concepts exist and the different primary energy carriers are characterized with an unclear basis, the CED is grouped into six categories for the Ecoinvent database and no aggregated value is presented. Common to all categories is the basis that all energy carriers have an intrinsic value. This intrinsic value is determined by the amount of energy withdrawn from nature (Frischknecht et al., 2007).

✓ Cumulative exergy demand (CExD) method

Exergy is another term to state the quality of energy in addition to energy content. Exergy is defined as “a measure for the useful work that a certain energy carrier can offer”. Accordingly, exergy is considered as a benchmark of the potential loss of “useful” energy resources.

The Cumulative Exergy Demand (CExD) indicator represents total exergy removal from nature to provide a product or service, including the exergy of all resources required. Thus, CExD implies the quality of energy demand and contains the exergy of energy carriers and also non-energetic materials. The resources contained in the Ecoinvent database are evaluated in terms of CExD, regarding chemical, kinetic, hydro-potential, nuclear, solar-radiative and thermal exergies. Similar to CED, CExD is grouped into eight categories for the Ecoinvent database and no aggregated value is presented. The category scores indicate the difference of the total exergy between all outputs and inputs to provide a process or service (Bösch et al., 2006).

2.1.3.2 Multiple issue methods

Single issue methods can be considered as ‘entry points’ into life cycle thinking but they do not provide comprehensive analysis. As stated for CED, single issue methods “make only sense in combination with other methods" (Kasser and Pöll, 1999). Multiple issue midpoint or endpoint methods are required for a detailed assessment. More reliable results can be obtained with such comprehensive methods, if information on the actual environmental burdens and especially on process-specific emissions are available.

Problem oriented (midpoint) impact assessment methods used are CML 2 baseline 2000 method (Guinée et al., 2002) and ReCiPe (H) method (Goedkoop et al., 2009). Moreover, ReCiPe (H) method is also applied from damage oriented (endpoint) perspective (Goedkoop et al., 2009).

- ✓ **CML 2 baseline 2000 method**

CML 2 baseline 2000 impact assessment method is applied to calculate several impact category scores considering the potential environmental damage of airborne, liquid and solid emissions with appropriate equivalence factors to selected reference compounds. CML 2 baseline 2000 impact assessment results are expressed in ten categories: abiotic depletion (mineral and fossil fuel), acidification, eutrophication, fresh water aquatic ecotoxicity, global warming (GWP100a) human toxicity, marine aquatic ecotoxicity, ozone layer depletion, photochemical oxidation, and terrestrial ecotoxicity (Guinée et al., 2002).

✓ ReCiPe method

ReCiPe is the combination of the previously published Eco-indicator 99 and CML impact assessment method. The aim of this integration is to assemble the ‘problem oriented approach’ of CML and the ‘damage oriented approach’ of Eco-indicator 99. As mentioned before (Section 2.1.3) the ‘problem oriented approach’ evaluates the impact categories at a midpoint level which decreases the uncertainty of the results. The drawback of this method is that the results are offered in a number of impact categories and so, it is difficult to draw conclusions from these complex indicators. ReCiPe method overcomes this problem with the implementation of both strategies by utilizing problem oriented (midpoint) and damage oriented (endpoint) impact categories. The midpoint characterization factors are multiplied by damage factors, to reach the endpoint characterization scores.

ReCiPe contains two levels of impact categories with their corresponding characterization factors. At the midpoint level, 18 impact categories are referred. To reach the endpoint level, most of these midpoint impact categories are multiplied with damage factors. The resulting scores are combined into three endpoint categories: human health, ecosystems and resource surplus costs. Then, these three endpoint categories are normalized, weighted, and aggregated into a single score. The evaluation of ReCiPe category scores is given in **Figure 2.4** starting from the inventory data to obtain 18 midpoint categories, then from midpoint categories to three endpoint categories, and finally, gathering endpoint categories to a single score.

The endpoint characterization factors used in ReCiPe method are explained below:

1. Human Health category scores are expressed as the number of year life lost and the number of years lived disabled. These two parameters are combined to get a single score defined as Disability Adjusted Life Years (DALYs). The unit is years.

2. Ecosystems category scores are expressed as the loss of species during a certain time, over a certain area. The unit is years.

3. Resources surplus costs category scores are expressed as the surplus costs of future resource production over an infinitive timeframe with the assumption of constant annual production and a 3% discount rate. The unit is 2000US$.

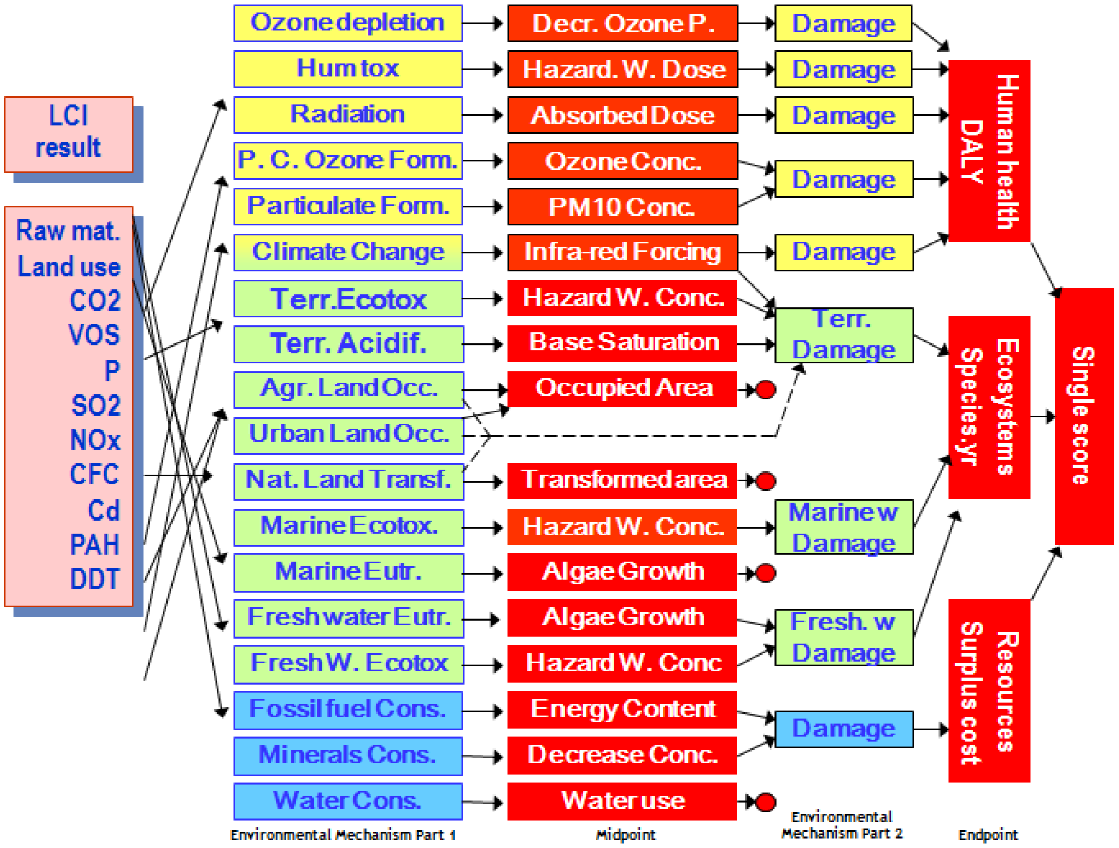


Figure 2.4 A schematic summary of ReCiPe methodology (SimaPro, 2016)

In order to reach a single score from inventory data, environmental mechanisms and damage models are used. These mechanisms have a particular level of uncertainties due to their incompleteness. Accordingly, models based on these mechanisms also have uncertainties. In ReCiPe method, different sources of uncertainty and different (value) choices are grouped into a number of perspectives or scenarios, with respect to the “Cultural Theory” concept previously published by Thompson (1990).

Three perspectives are determined: individualist (I), hierarchist (H), and egalitarian (E). These perspectives are merely used to group similar types of assumptions and choices rather than representing archetypes of human behaviour. Perspective I is based on the short-term interest, impact types that are undisputed, technological optimism regarding human adaptation. Perspective H is based on the most common policy principles regarding time-frame and other issues. Perspective E is the most precautionary perspective, considering the longest time-frame, impact types that are not yet fully established but for which some indication is available.

The hierarchist version of ReCiPe with average weighting is chosen for this study since value choices made in this version are scientifically and politically accepted, in general.

2.1.4 Interpretation

The last phase of LCA includes the evaluation of the results from either inventory analysis or impact assessment in comparison with the goal of the study defined in the first phase, the proposal of recommendations, and the final reporting of the results.

2.2 Scenario Analysis

Future energy mix decisions are dominated by the following factors: meeting the increasing electricity demand and reducing the high dependence on imported fuels. In order to reflect the possible future electricity generation alternatives, three different scenarios are introduced for both years 2023 and 2030. Future scenarios are based on the publication by WWF-Turkey supported by European Climate Foundation and collaborated with BNEF (WWF, 2014). Electricity demand projections and electricity generation mix estimations are given in **Figure 2.5** and **Figure 2.6**, respectively. Future demands for fossil fuels are estimated via linear regression according to the installed power projections. Installed power estimates for future scenarios are given in **Table 2.4**.

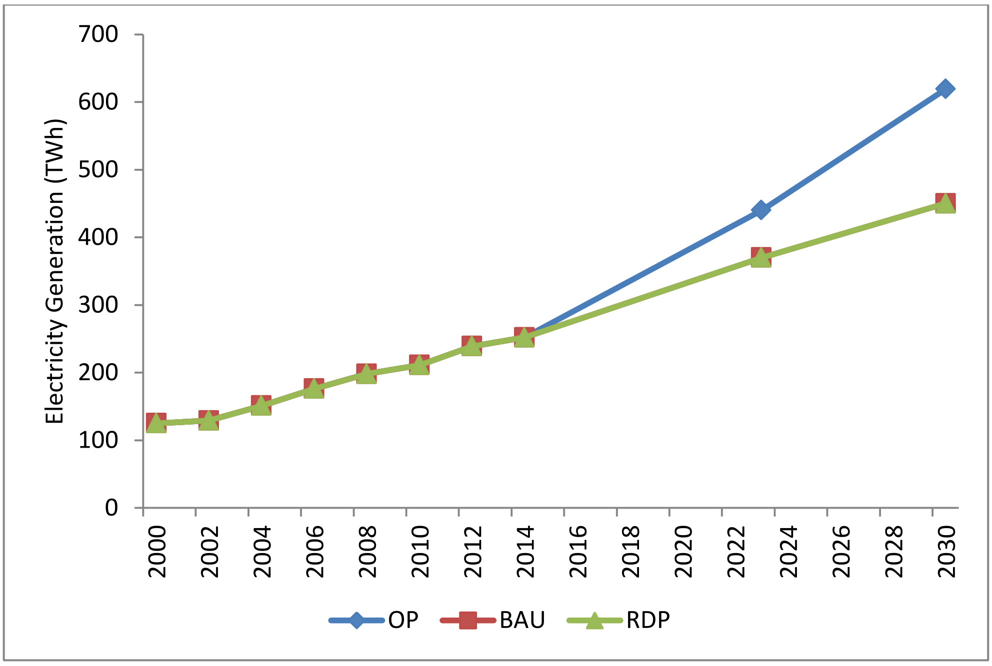


Figure 2.5 Electricity demand estimations according to future scenarios (WWF, 2014)

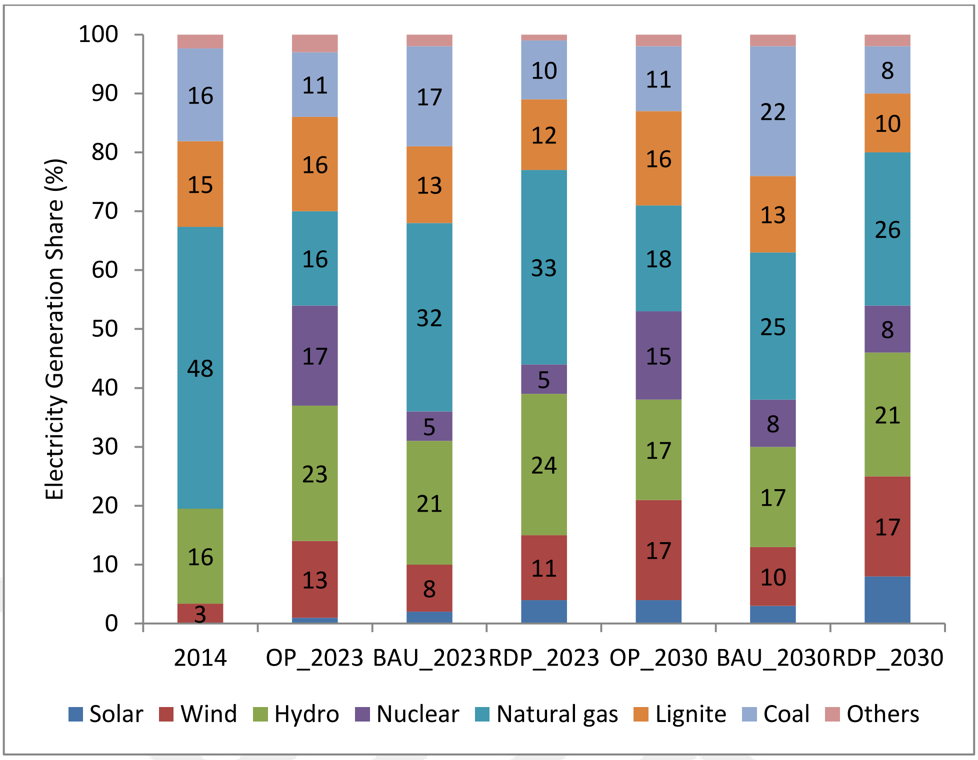


Figure 2.6 Electricity mix estimations according to future scenarios (WWF, 2014)

Table 2.4 Installed power projections for future scenarios (MW)

		OP		BAU		RDP	
	2014	2023	2030	2023	2030	2023	2030
Natural gas	21476	25000	25000	27920	27920	27920	27920
Hard Coal	6533	8755	12257	12108	19318	6672	6672
Lignite	8693	16245	22743	10478	13059	9741	9741
Hydro	23643	36000	36000	27434	27434	30459	33968
Wind	3630	20000	38000	10302	15902	13980	26883
Solar	40	3000	16000	5500	10050	10091	23546
Nuclear	0	9600	12000	2400	4800	2400	4800

2.2.1 Official plans (OP)

Official plans scenario (OP) is based on the targets of the government assuming 5.25% increase in the annual electricity demand through the next 15 years. In respond to this increase, mainly coal, additionally nuclear, hydroelectricity and other renewable sources are considered to have increasing shares while natural gas share drops from 48% to

18%. According to this scenario, electricity demand in 2023 and 2030 are assumed to be 440 TWh and 619 TWh, respectively.

2.2.2 Business-as-usual (BAU) scenario

Current policies or business-as-usual scenario (BAU) assumes the annual electricity demand increase rate is not as high as 5.25% but rather 25% lower than this value due to the statistics about developing countries stating that the annual electricity demand increase rate declines as the level of welfare increases. It is predicted that coal and lignite shares significantly increase as natural gas share decreases. According to this scenario, electricity demand in 2023 and 2030 are assumed to be 370 TWh and 450 TWh, respectively.

2.2.3 Renewables development pathway (RDP)

Renewables development pathway scenario (RDP) is based on most of the assumptions made in current policies scenario. The main difference between two scenarios is the substitution of coal and lignite with renewable energy sources. According to this scenario, electricity demand in 2023 and 2030 are assumed to be 370 TWh and 450 TWh, respectively.

2.3 Multi Criteria Decision Analysis (MCDA)

Sustainable energy decision-making requires the comparison of energy generation technologies regarding a wide range of financial, technical, environmental, and socio-economic criteria. Even there is not a standardized methodology for sustainability evaluation of the energy systems; the most widely used approach is the MCDA method. “MCDA is a quantitative tool that enables decision-makers to handle complex energy management problems” (Wang et al., 2009). The flow sheet of the methodology applied is given schematically in **Figure 2.7**.

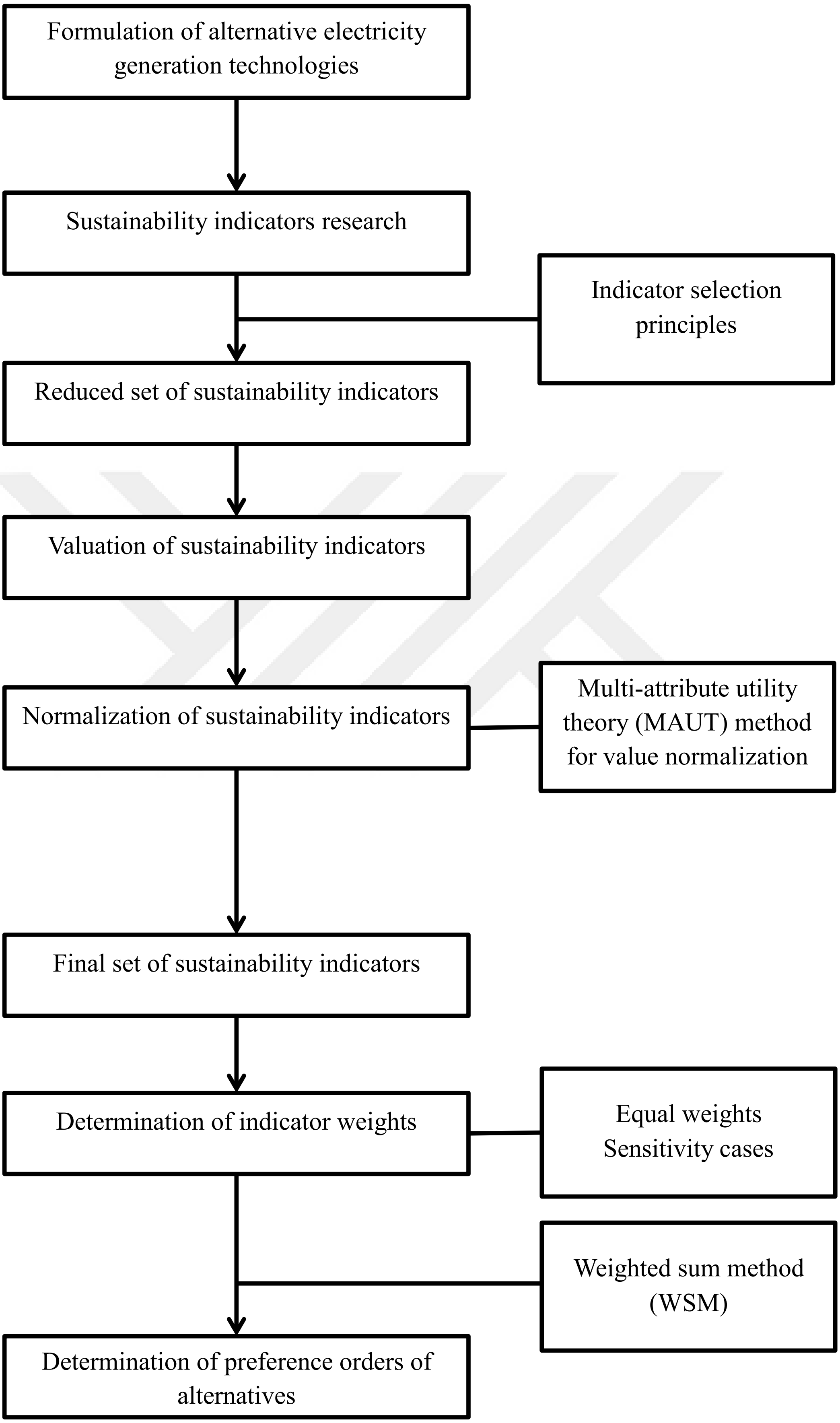


Figure 2.7 MCDA process in sustainable energy decision-making [adapted from (Maxim, 2014; Wang et al., 2009)]

2.3.1 Identification of the electricity generation technologies

In order to determine the electricity generation technologies, the extensive work of Breeze (2005) is examined. The electricity generation alternatives in **Table 2.5** are based on the commercially-available and/or promising technologies contributing to Turkey electricity generation mix for 2014**.** Fossil fuels are the main components of electricity sector, but recently renewable energy shares tend to increase. Even solar PV has very small share in the total mix in 2014; up to 2016 its share increased sixty fold. For this reason, promising renewable energy technologies are considered in addition to conventional fossil fuel resources (TETC, 2014).

Table 2.5 Electricity generation alternatives included in MCDA for the year 2014

Alternative	Resource/Fuel	Characteristics
Natural gas	Natural gas	Combined cycle gas turbine plants
Coal	Imported and domestic coal	Steam turbine based pulverized coal plants
Hydro (dam)	Water flow	Reservoir (dam) plants
Hydro (r-o-r)	Water flow	Run-of-river (r-o-r) plants
Wind	Wind	Onshore wind farms
Solar PV	Solar radiation	Photovoltaic solar panels

Natural gas is the biggest contributor to electricity generation although it has serious drawbacks in terms of environmental and social aspects. Natural gas power plants have two types of operation characteristics: conventional steam turbine (CST) and combined cycle gas turbine (CCGT) power plants. Majority of the natural gas power plants in Turkey are CCGT with an installed power share of 90%; and the left 10% is CST power plants. The study is mainly based on the calculations for CCGT power plants since its high share in the generation mix.

Due to its relatively low cost, domestic coal is preferred extensively for the electricity generation activities. Even, 2012 is declared as the “coal year” and the domestic coal mines are operated at full capacity resulting in catastrophic Soma accident. Coal used in the electricity generation is supplied from both domestic resources and importer countries. In 2014, electricity generated from domestic coal is almost equal to the generation from imported coal. So, the indicator results are calculated as the weighted sum of scores of each coal type.

Hydropower technologies are amongst the oldest and cheapest electricity generation methods. In Turkey, two types of hydropower technologies are employed: reservoir (dam) and run-of-river (r-o-r). The two technologies are utterly different than each other in design, operation and impact assessment; for this reason they are examined in separate topics.

Wind is one of the developing renewable energy technologies of which Turkey has a very high electricity generation potential. Onshore wind power plants have been utilizing in various regions of Turkey with a growing capacity, recently.

Even not having a share of greater than one in a ten thousand in the year 2014, solar technologies are essential for electricity generation since its high potential for Turkey. Solar energy can be employed for electricity generation in two ways: solar thermal and solar photovoltaic panels. Although its share is very small in electricity generation mix, solar PV technology is examined as an alternative renewable energy source due to its increasing share with respect to sustainability issues.

2.3.2 Selection and valuation of the sustainability indicators

As Wang et al (2009) mentioned in their extensive review, there exist numerous sustainability indicators in the literature. In this study, the most widely used indicators are chosen in an attempt to cover a broad range of sustainability concerns specific to electricity generation technologies. Indicator selection methods are basically considered in two groups: methods based on subjectivity and rational methods (Ibáñez-Forés et al., 2014). In this study we choose “own opinion” method from methods based on subjectivity. The list of all available indicators, which have been mentioned extensively in the previously published study, is investigated (Wang et al., 2009). Then, the indicators appropriate for the study are selected with respect to the opinions of experts in energy management applications as well as the previously published papers. The selection is made via considering the following principle mentioning that an indicator should be systemic, consistent, independent, measurable, and comparable (Wang et al., 2009). The reduced set of twelve indicators is examined in four criteria groups: economic, technical, environmental, and socio-economic (**Table 2.6**).

While economic, technical, and socio-economic indicators are gathered from the literature, environmental impacts are calculated via life cycle approach following the ISO guidelines.

2.3.3 Normalization of the sustainability indicators

Since quantitative and qualitative indicators have different characteristics, it is required to establish a common basis for the evaluation. In order to compare the indicator values with different magnitudes, normalization process has to be carried out. There are three groups of methods for normalizing the chosen indicators, namely own analytical methods, distance-to-target methods, and linear normalization methods (Ibáñez-Forés et al., 2014, Kumar et al., 2017). Since this is a multi-criteria evaluation study and it is not possible to find a reference "target" data for each indicator; a linear normalization method is preferred. Among the linear normalization methods, MAUT method, also known as min-max method, is used to calculate a utility value for each indicator due to its easiness to apply. First, indicators are classified according to their benefit attribution (see **Table 2.6**), and then utility values varying between 0 and 1 are calculated via two different equations:

Positive attribute: $u_{ij}=(x_{ij}-x_{min})/(x_{max}-x_{min})$ (2.1)

Negative attribute: $u_{ij}=(x_{max}-x_{ij})/(x_{max}-x_{min})$ (2.2)

where u_{ij} is the utility value for the j-th criteria of the i-th indicator; x_{ij} is the indicator value for the j-th criteria of the i-th indicator ; x_{min} the minimum value of the indicator; x_{max} is the maximum value of the indicator (Maxim, 2014).

Table 2.6 Selected evaluation criteria and sustainability indicators

Criteria	*i*	Indicators	Definition	Benefit attribute
Economic	1	Levelized Cost Of Electricity (LCOE)	The average cost of producing electricity over the entire lifetime of the unit; it takes into account all investment, operation and maintenance, fuel, decommissioning and even CO_2 emissions cost	Negative
Technical	2	Efficiency	The ratio between the useful electricity output from the generating unit, in a specific time, and the energy value of the energy source supplied to the unit in the same time period	Positive
	3	Flexibility	The ability to respond to fluctuations in demand and to insure overall grid stability in the long term in the context of growing share of intermittent generation from some renewable energy sources	Positive
	4	Electricity mix share	The electricity generation share of the selected technology	Positive
	5	Capacity factor	The ratio of the net electricity generated, for the time considered, to the energy that could have been generated at continuous full-power operation during the same period.	Positive
Environmental	6	Climate change	The global warming potential calculated in CO_2 equivalent	Negative
	7	Ozone depletion	The destruction of the stratospheric ozone layer by anthropogenic emissions of ozone depleting substances	Negative
	8	Natural land transformation	The amount of natural land transformed and occupied for a certain time	Negative
Socio-economic	9	Job creation	Job-years of full time employment created over the entire lifecycle of the unit	Positive
	10	Social acceptability	Public preference for the deployment or utilization of a certain electricity generation technology	Positive
	11	Accident-related fatality	Deaths from accidents involved in the entire lifecycle of the unit	Negative
	12	Primary energy and technology dependence	The extent to which an economy relies upon imports in order to meet its energy needs	Negative

2.3.4 Assigning indicator weights regarding the different sensitivity cases

Indicator weights are assigned to show the relative importance of indicators amongst the others. Different weighting preferences directly influence the MCDA results. For this reason, weighting should be determined carefully. Weighting methods are examined in two groups: objective and subjective weighting methods. In order to avoid the subjectivity, we prefer to use objective weighting methods.

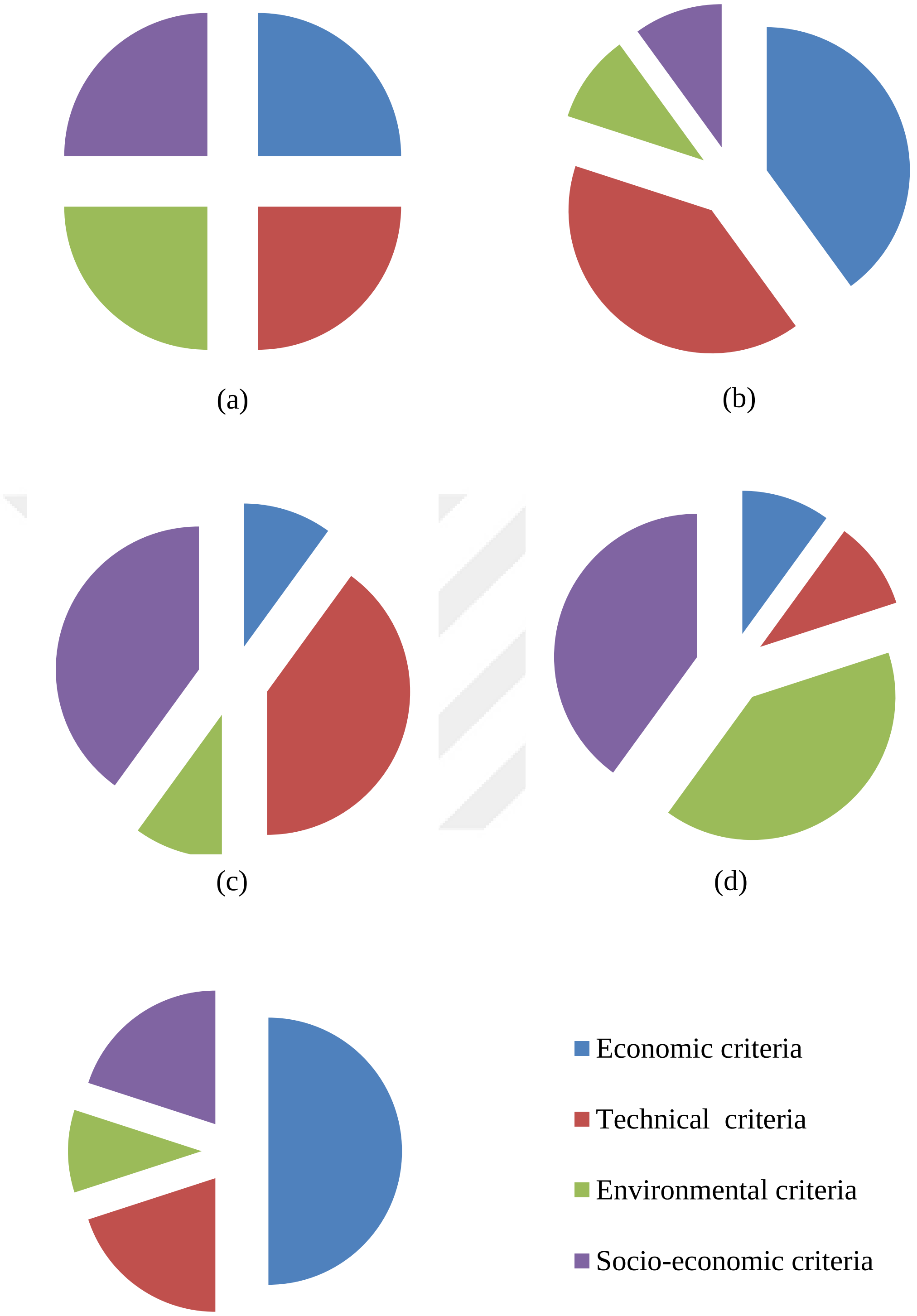
The most common weighting method in energy system decision making is the equal weights method (Wang et al., 2009). In this study, in order to compare different preference scenarios, equal weights and additional four cases are analysed: "holistic approach" where indicators have the same weight; "technocratic approach" mainly focusing on financial and technical indicators; "mercantilist approach" where technical and socio-economic indicators dominate; "eco-social approach" mentioning environmental and socio-economic indicators (Brand and Missaoui, 2014) and "administrative approach" with strong emphasis on financial, technical and socio-economic indicators (**Figure 2.8**).

2.3.5 Ranking of the electricity generation technologies

Final step of the methodology is to determine the preference orders of the alternative electricity generation options according to their corresponding weights. Weighted sum method (WSM) is the most commonly used approach in sustainable energy systems decision-making. The score of a technology is calculated as

$$S_i = \sum_{j=1}^{n} w_i u_{ij}, \quad i=1, 2,..., m \tag{2.3}$$

where u_{ij} is the utility value for the j-th criteria of the i-th indicator, w_i is the weight of the indicator. Then the resulting cardinal scores for each technology can be used to rank, screen, or choose an alternative. The best alternative is the one whose score is the maximum (Wang et al., 2009).



(a) (b)

(c) (d)

(e)

Figure 2.8 Weighting preferences for different sensitivity cases, (a) Holistic approach (b) Technocratic approach (c) Mercantilist approach (d) Eco-social approach (e) Administrative approach

3 RESULTS AND DISCUSSION

Life cycle assessment and multi-criteria decision analysis methodology results are presented and discussed in this section. LCA methodology is applied for the electricity generation in 2014 as the basis year and also three different future scenarios are compared for the years 2023 and 2030 while MCDA methodology is applied for the electricity generation technologies present in the year 2014.

3.1 Life Cycle Assessment (LCA)

Environmental impacts of electricity generation technologies are investigated via Life Cycle Assessment (LCA) methodology. As mentioned before (Section 2.1), LCA includes four phases connected with each other. The *interpretation* phase is the detailed investigation, analysis and reporting of the results in accordance with goal and scope definition phase. In this section, interpretations related to inventory analysis and impact assessment are to be discussed.

3.1.1 Inventory analysis and interpretation

The most challenging part of a LCA study is inventory analysis since it is very critical to find adequate country-specific data to construct the model for selected generation technologies. First a general scheme of electricity generation profile is drawn for both total generation levels (**Figure 3.1**) and for generation technology shares (**Figure 3.2**).

As clearly seen in the figures, Turkey electricity sector is highly dependent on fossil fuel technologies. But this trend is about to change thanks to Paris Agreement (2015) taking measures against climate change mitigation by reducing fossil fuel consumption. In order to accomplish this mission, conducting comprehensive analyses and developing down-to-earth plans are crucial in decision making processes for sustainable energy systems. For this purpose, future scenarios are investigated from an environmental point of view. Total energy demand projections tend to increase by 2023 and 2030 in agreement with the population growth and increase in the level of welfare (**Figure 2.5**). Also the shares of electricity generation technologies in the future scenarios are presented in **Figure 2.6**.

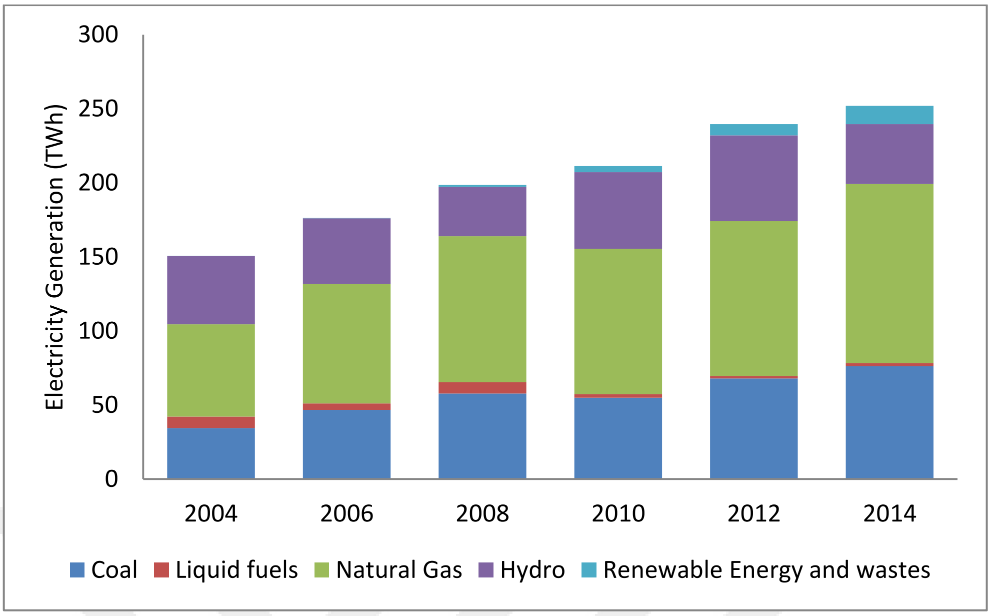


Figure 3.1 Electricity generation profile in Turkey (2004-2014) (TETC, 2014)

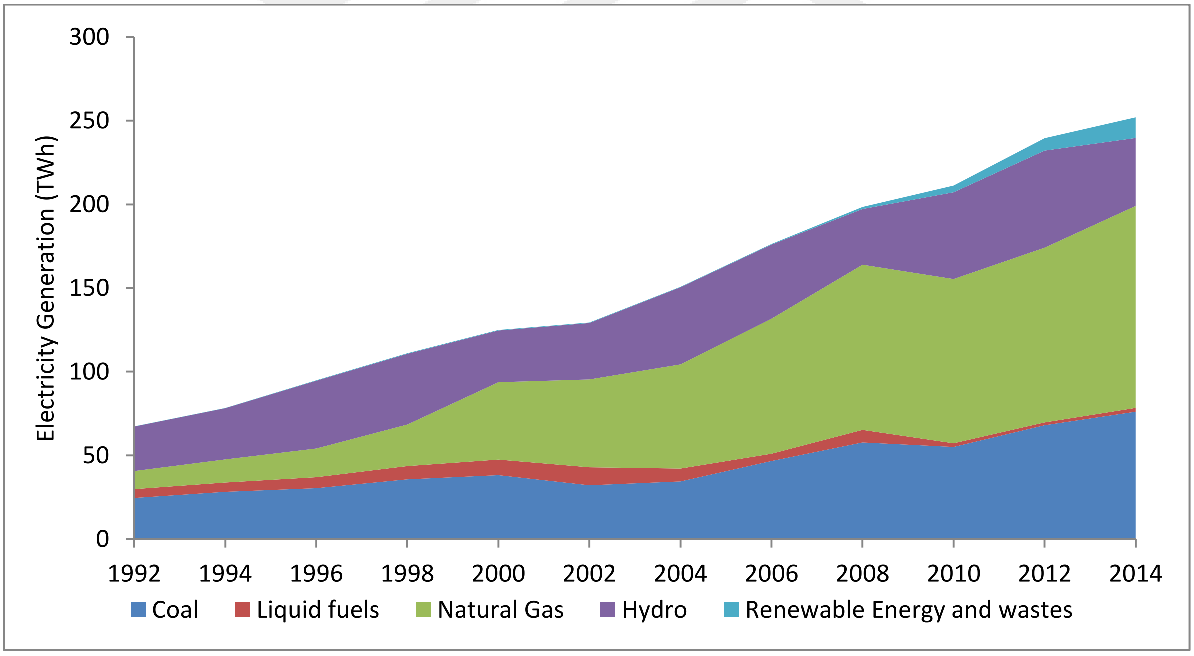


Figure 3.2 Electricity generation from primary energy sources (TETC, 2014)

3.1.2 Impact assessment and interpretation

Potential environmental impacts of the studied technologies are calculated in the impact assessment phase according to the method selected. In this study, the most studied single and multiple issue impact assessment methods are employed.

Single issue methods can be good ‘entry points’ into life cycle thinking with respect to a specific impact category. In order to have a brief analysis about the generation alternatives IPCC 2013 GWP, CED, CExD single issue methods are employed.

As mentioned before, single issue methods consider a limited series of input data and may leave out significant impact categories. Thus, multiple issue methods are also employed for comprehensive analysis of all relevant impacts associated with electricity generation. Selected multiple issue methods are CML 2 Baseline 2000, ReCiPe (H) midpoint and ReCiPe (H) endpoint. CML 2 Baseline 2000 methodology has been one of the most preferred midpoint approaches, recently. But as the ReCiPe methodology is introduced with both midpoint and endpoint categories, it is expected to be applied more comprehensively.

3.1.3 Analysis of the current situation

2014 is selected as the basis year because in the beginning of this study, it has been the latest year verified data was available. At first, 2014 year is investigated as the current situation and the results established a standpoint for comparisons of the future scenarios. The results and discussion of the methods used are given below.

3.1.3.1 IPCC 2013 global warming potential (GWP 100a)

Global Warming Potential (GWP) is the indicator of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2). Almost all of the equivalent emissions of CO_2 are resulted from fossil fuels due to their high carbon content (See Appendix A2). In order to limit the CO_2 emissions, countries are shifting from fossil fuel technologies to low-carbon policies; this shift is possible via the utilization of renewable energy technologies. As seen in **Figure 3.3**, in terms of global warming potential, renewable energy resources have considerably low scores.

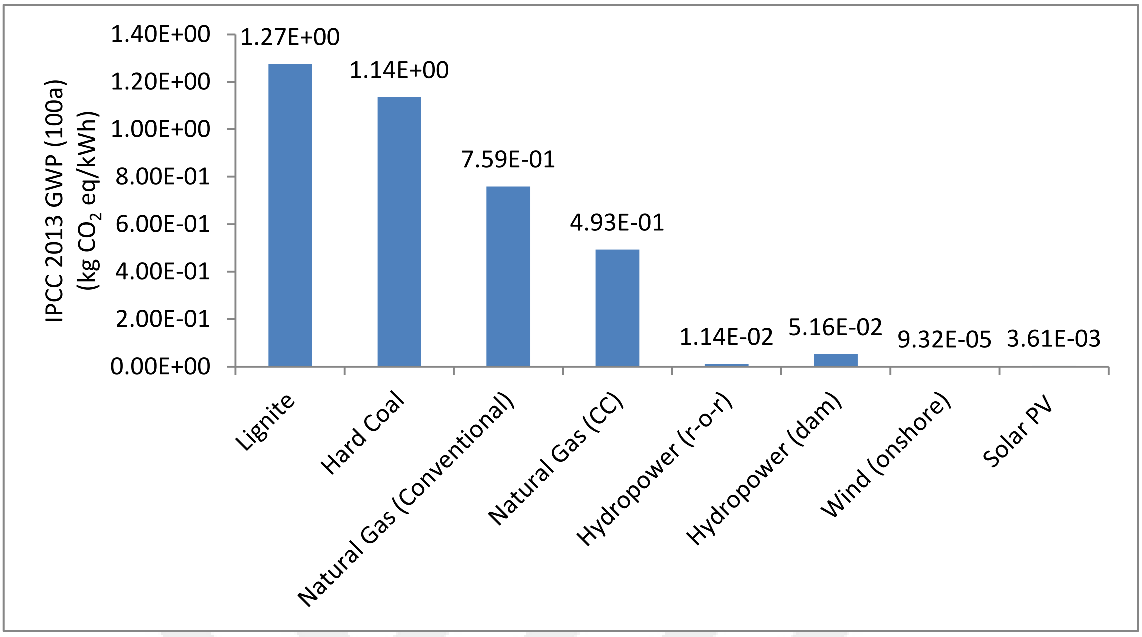


Figure 3.3 IPCC 2013 GWP results for the year 2014

3.1.3.2 Cumulative energy demand (CED)

Cumulative Energy Demand (CED) is a tool for measuring the amount of energy needed from the nature for the selected process. CED is examined in six subcategories, only related categories are included in the computations. The computed results are discussed for the associated three categories as explained below (See Appendix A3). CED scores are mainly used for comparisons with the future projections.

Non-renewable, fossil CED is very high for fossil fuel technologies both using coal and natural gas. As seen in the **Figure 3.4**, non-renewable fossil energy demand scores for renewable energy technologies are quite lower than fossil fuels.

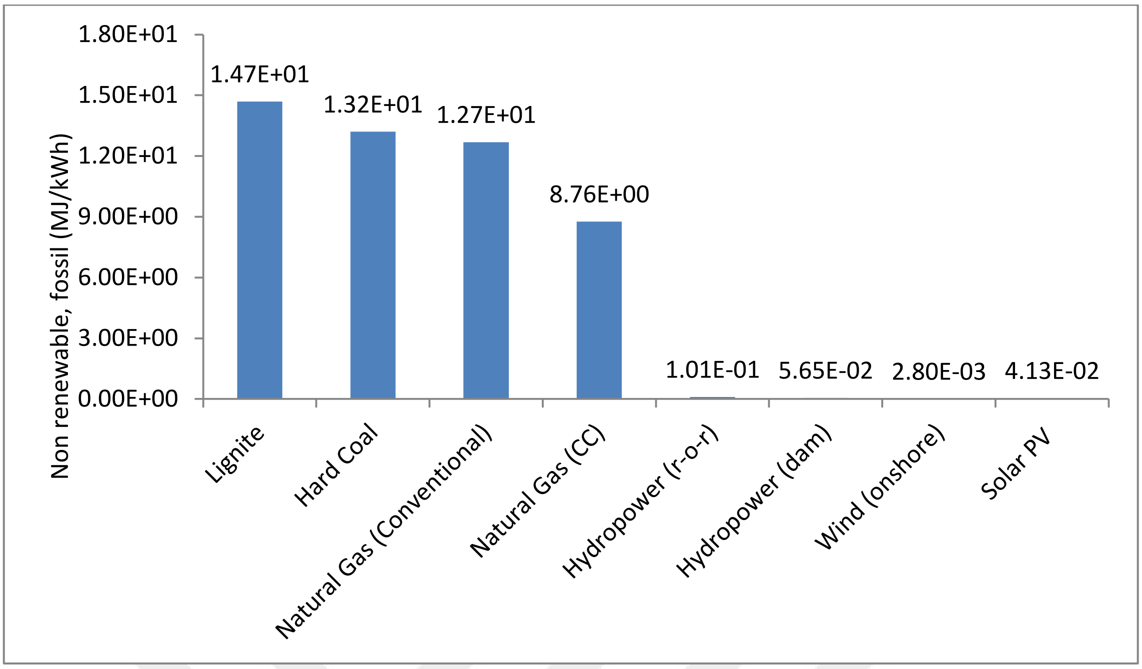


Figure 3.4 Non-renewable, fossil CED results for the year 2014

Renewable, wind, solar CED scores are high for the technologies they consider. As seen in the **Figure 3.5**, energy demand for wind and solar is quite high compared to other technologies.

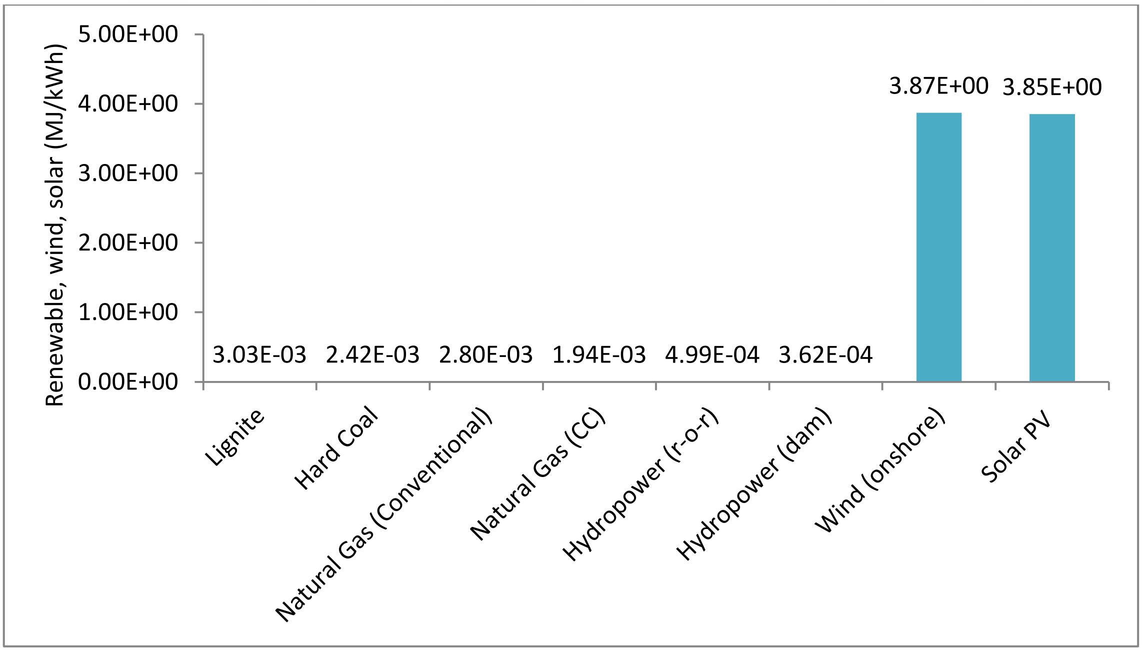


Figure 3.5 Renewable, wind, solar CED results for the year 2014

Renewable, water CED scores are high for the technologies they consider. As seen in the **Figure 3.6**, energy demand scores for hydropower with dam and hydropower run-of-river type are quite high compared to other technologies.

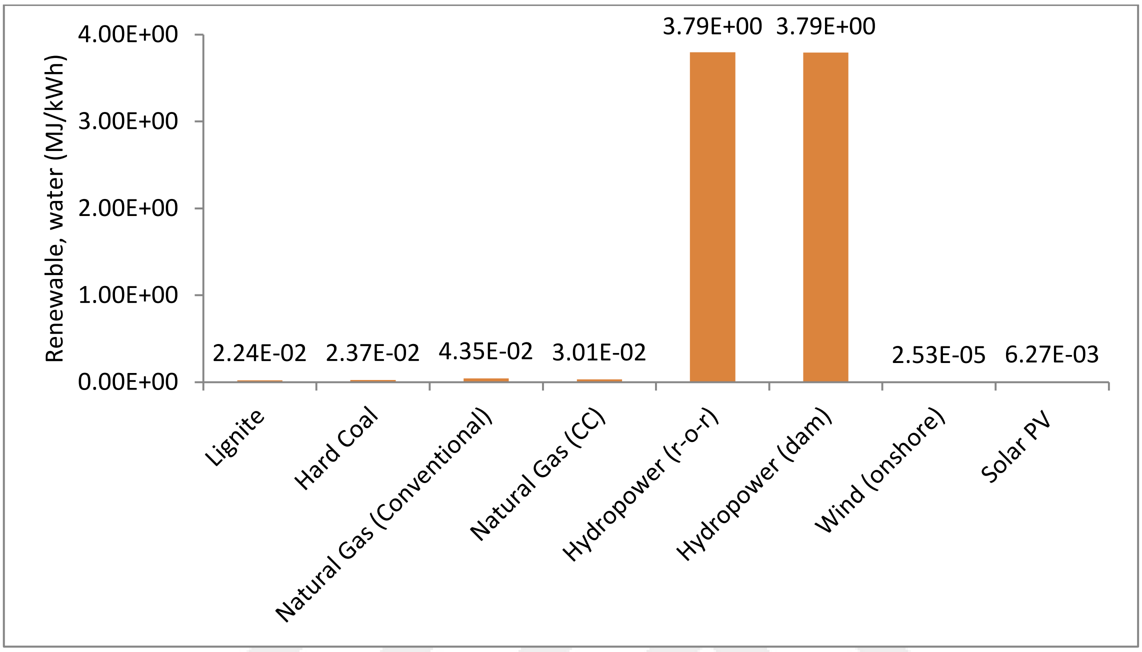


Figure 3.6 Renewable, water CED results for the year 2014

3.1.3.3 Cumulative exergy demand (CExD)

Cumulative Exergy Demand (CExD) is a tool indicating the sum of exergy of all resources required to provide a process or product. CExD is examined in 10 different impact categories but only related categories are included in the computations. CExD results show similar trend with CED scores and are discussed in the associated eight categories as explained below (See Appendix A4). CExD scores are mainly used for comparisons with the future projections

Non-renewable, fossil CExD is very high for fossil fuel technologies both using coal and natural gas. As seen in the **Figure 3.7**, non-renewable fossil energy demand scores for renewable energy technologies are quite lower than fossil fuels.

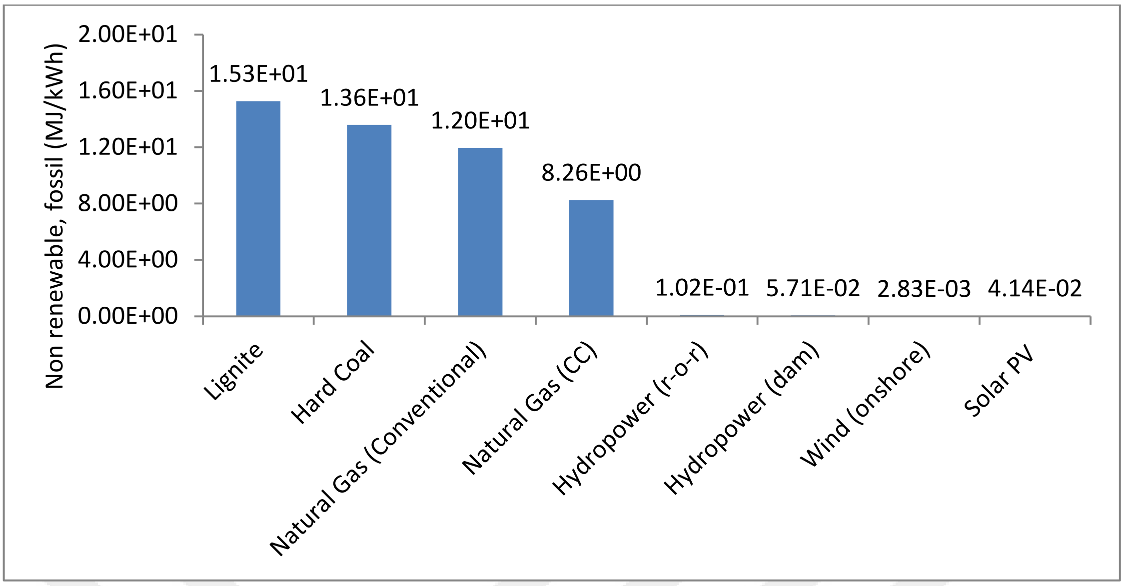


Figure 3.7 Non-renewable, fossil CExD results for the year 2014

Renewable, kinetic CExD is high for the technology it considers, namely wind technology (**Figure 3.8**).

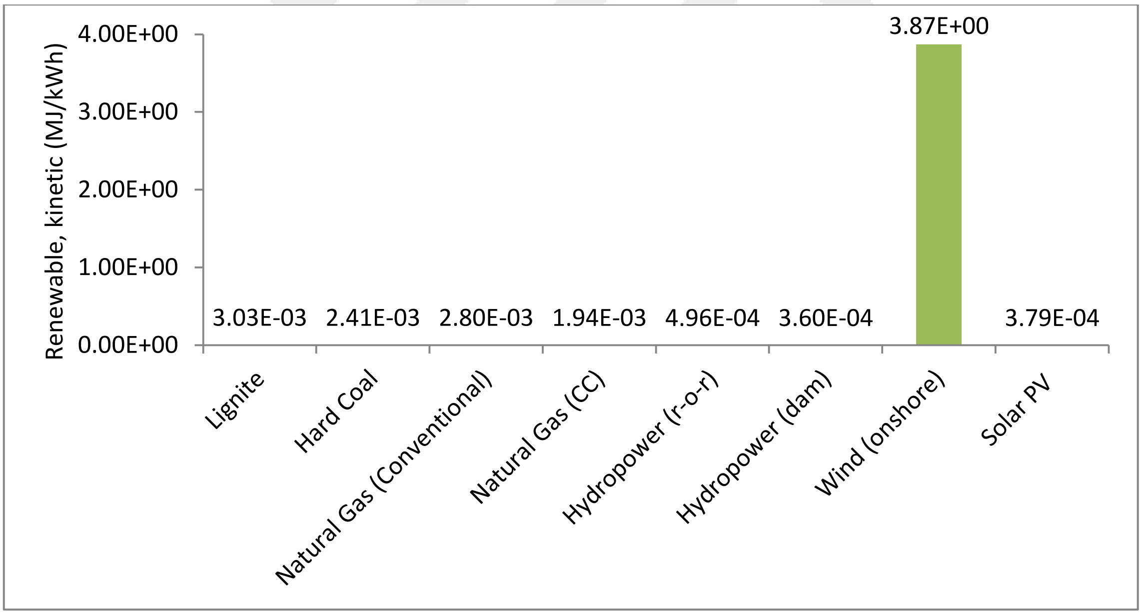


Figure 3.8 Renewable, kinetic CExD results for the year 2014

Renewable, solar CExD score is 3.58 MJ/kWh for solar PV technology (**Figure 3.9**).

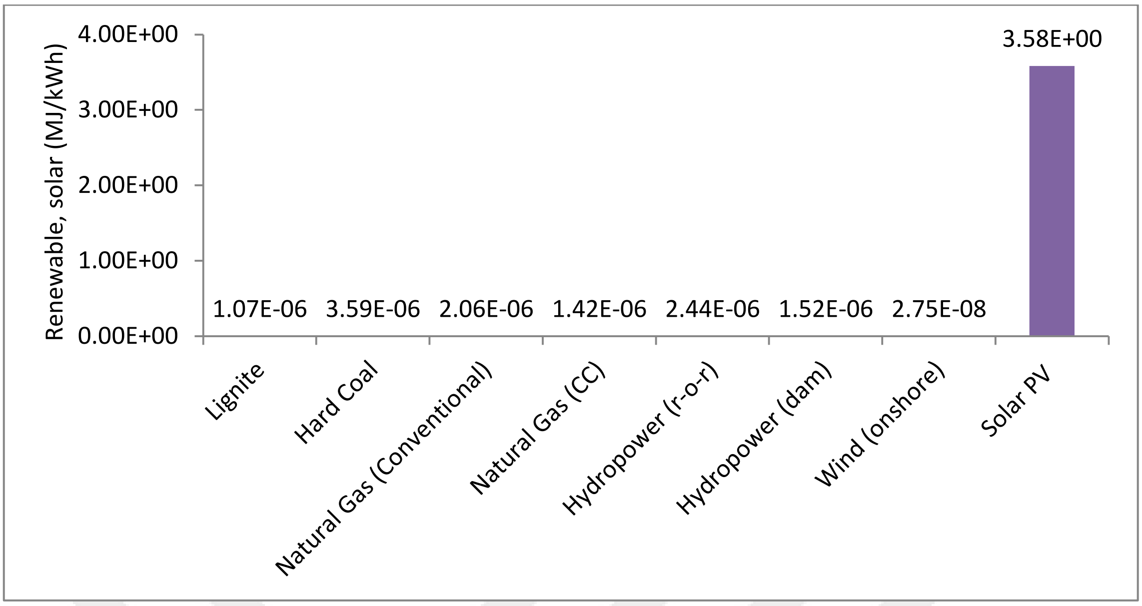


Figure 3.9 Renewable, solar CExD results for the year 2014

Renewable, potential CExD for hydropower with dam and run-of-river technologies are the same and equal to each other, 3.79 MJ/kWh (**Figure 3.10**).

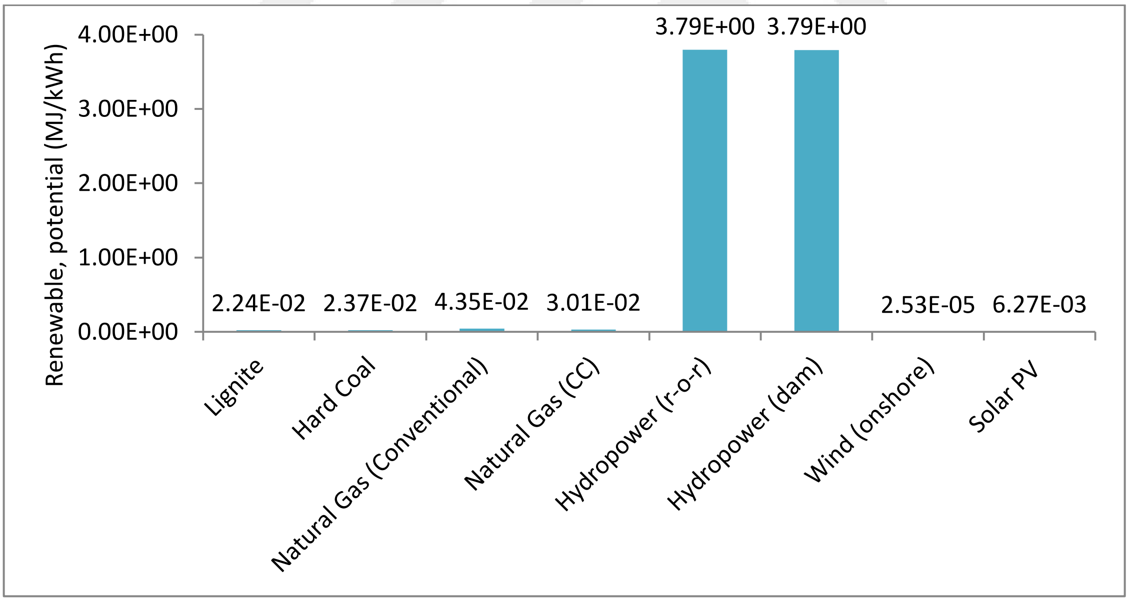


Figure 3.10 Renewable, potential CExD results for the year 2014

Non-renewable, primary CExD scores for natural gas technologies have the highest scores followed by hard coal and lignite. Renewable technology scores are ranked as solar PV, hydropower and wind (**Figure 3.11**).

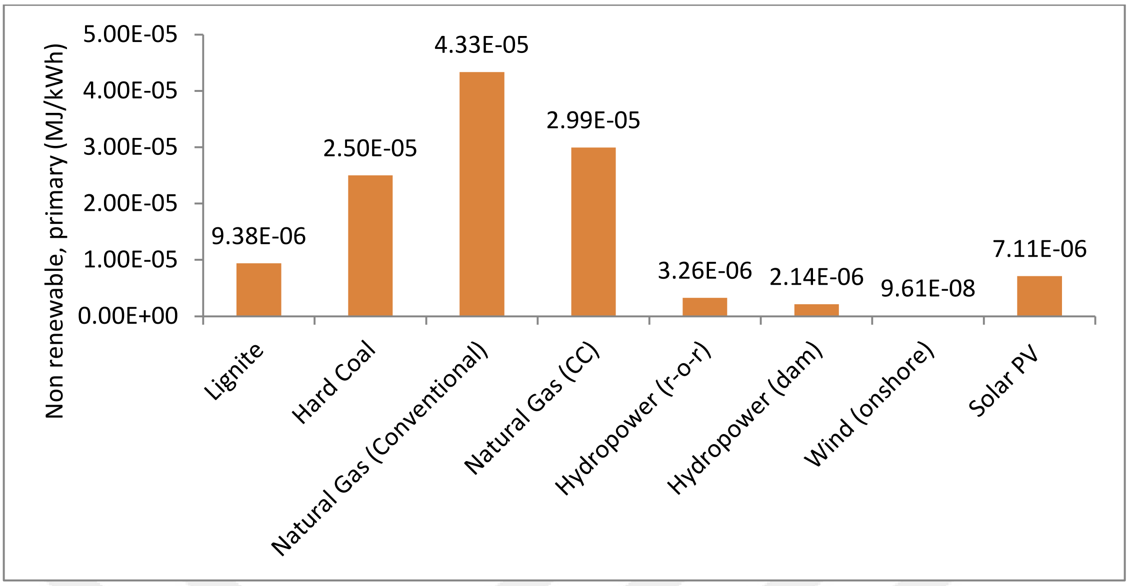


Figure 3.11 Non-renewable, primary CExD results for the year 2014

Renewable, water CExD for hydropower with dam has the highest value among the other technologies (**Figure 3.12**). Natural gas technologies have negative scores implying a decrease in the water consumption and positive effect on the environment. When the exergy content of released water is greater than the extracted fresh water, negative scores are obtained. This is mainly due to the cooling activities during LNG processing.

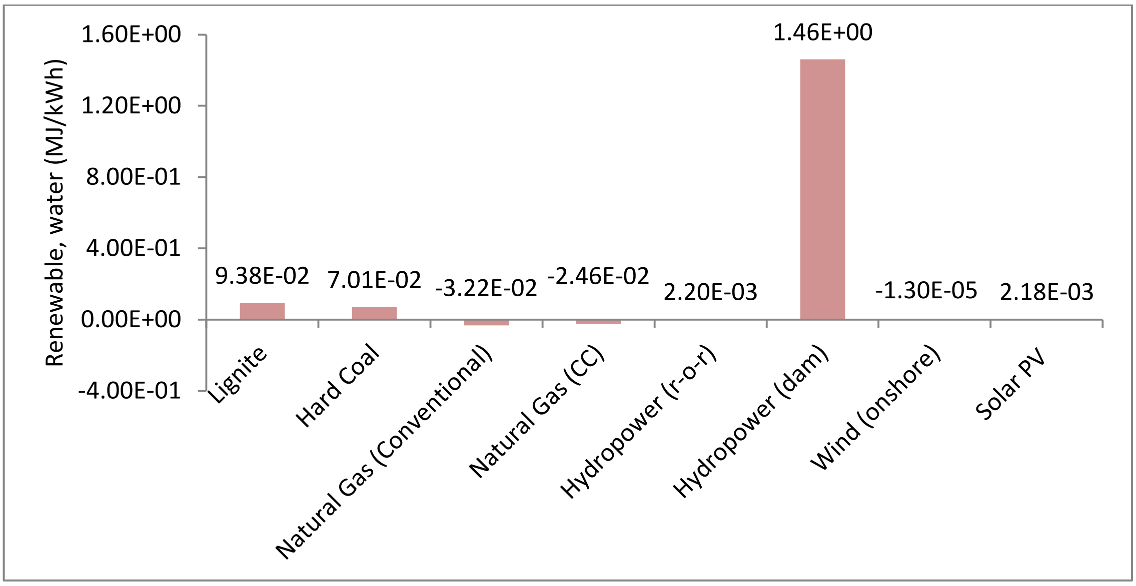


Figure 3.12 Renewable, water CExD results for the year 2014

Non-renewable, metals CExD scores are ranked as run-of-river hydropower, conventional natural gas, combined-cycle natural gas, hydropower with dam, hard coal, lignite, solar PV and wind (**Figure 3.13**).

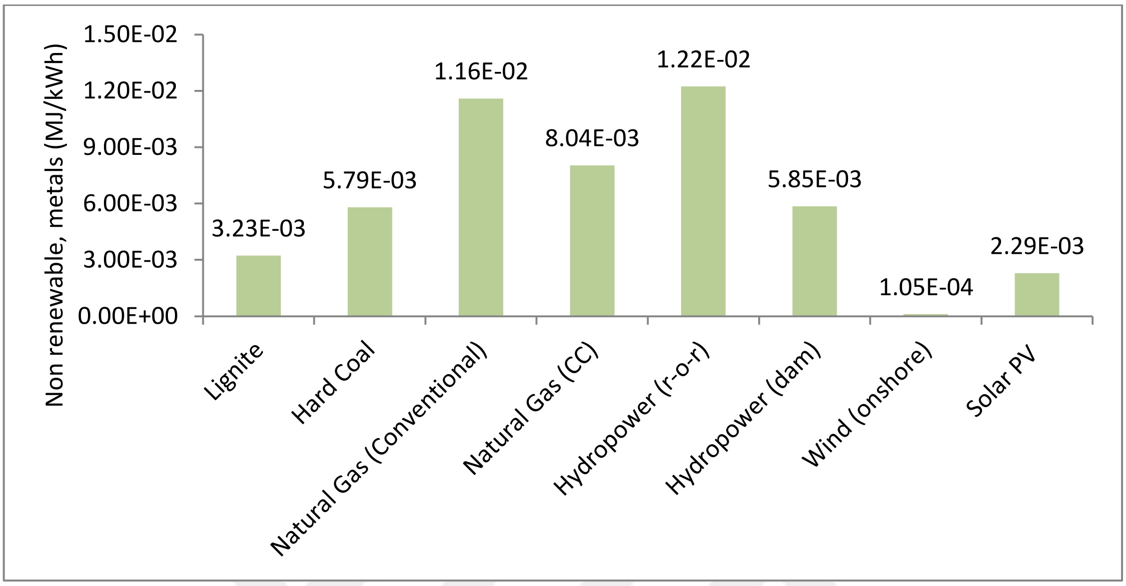


Figure 3.13 Non-renewable, metals CExD results for the year 2014

Non-renewable, minerals CExD scores have the highest values for hydropower technologies. Natural gas, hard coal, lignite, solar PV and wind follow the ranking (**Figure 3.14**).

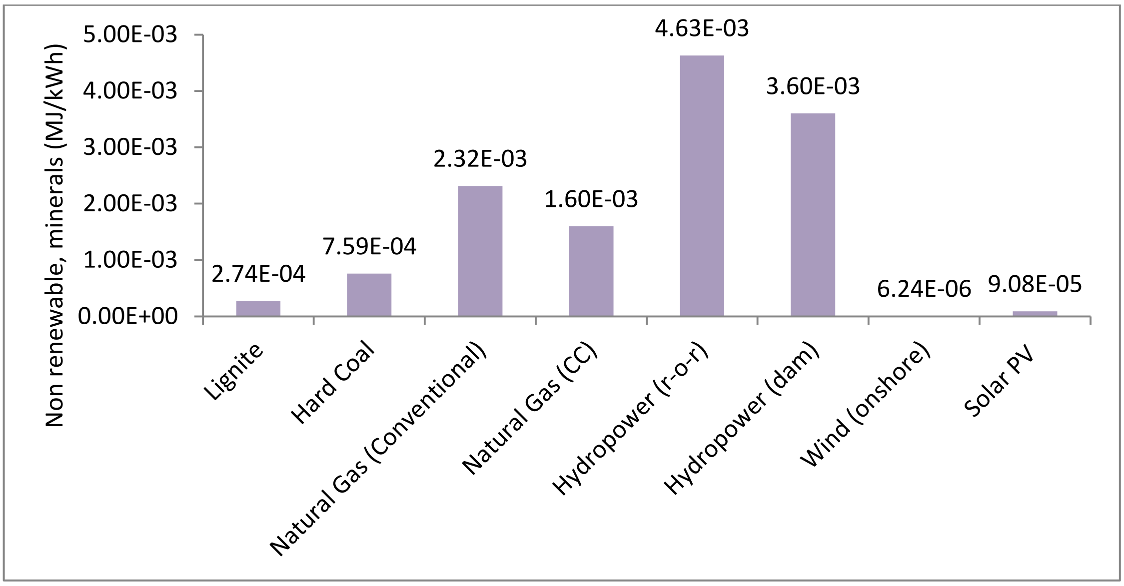


Figure 3.14 Non-renewable, minerals CExD results for the year 2014

3.1.3.4 CML 2 baseline 2000

CML 2 Baseline 2000 method results are expressed in ten categories: abiotic depletion (mineral and fossil fuel), acidification, eutrophication, fresh water aquatic ecotoxicity, global warming (GWP100a), human toxicity, marine aquatic ecotoxicity, ozone layer depletion, photochemical oxidation, and terrestrial ecotoxicity (See Appendix A5).

Abiotic depletion is allied with human wellbeing, human health and ecosystem health. This category scores result from extraction of minerals and fossil fuels. Accordingly, fossil fuel technologies lignite, coal, and natural gas have higher scores than renewable technologies (**Figure 3.15**).

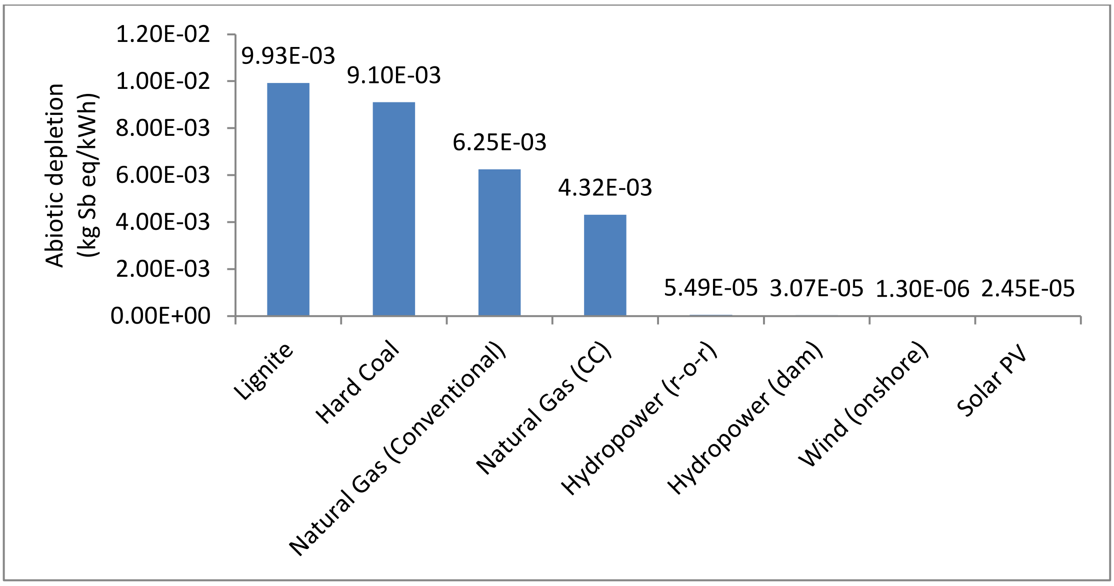


Figure 3.15 Abiotic depletion category scores for CML 2 Baseline 2000 method

Acidification describes the fate and deposition of acidifying substances mainly due to their high sulphur content. Acidification category results show that lignite has the highest score followed by hard coal and natural gas. Similar to abiotic depletion scores, renewable technologies have lower impacts than fossil fuel technologies (**Figure 3.16**).

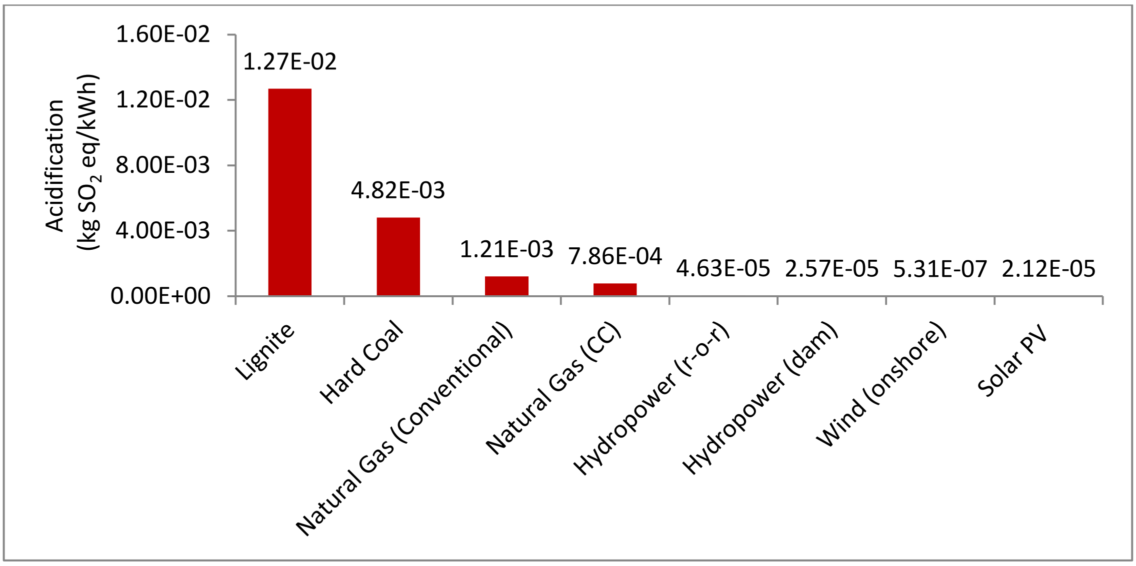


Figure 3.16 Acidification category scores for CML 2 Baseline 2000 method

Eutrophication includes all impacts due to excessive levels of macro-nutrients in the environment caused by emissions of nutrients to air, water and soil while operation of the power plant. This category results show similar trend with acidification and lignite has the highest score. The results reveal that renewable technologies have lower scores than fossil fuel technologies (**Figure 3.17**).

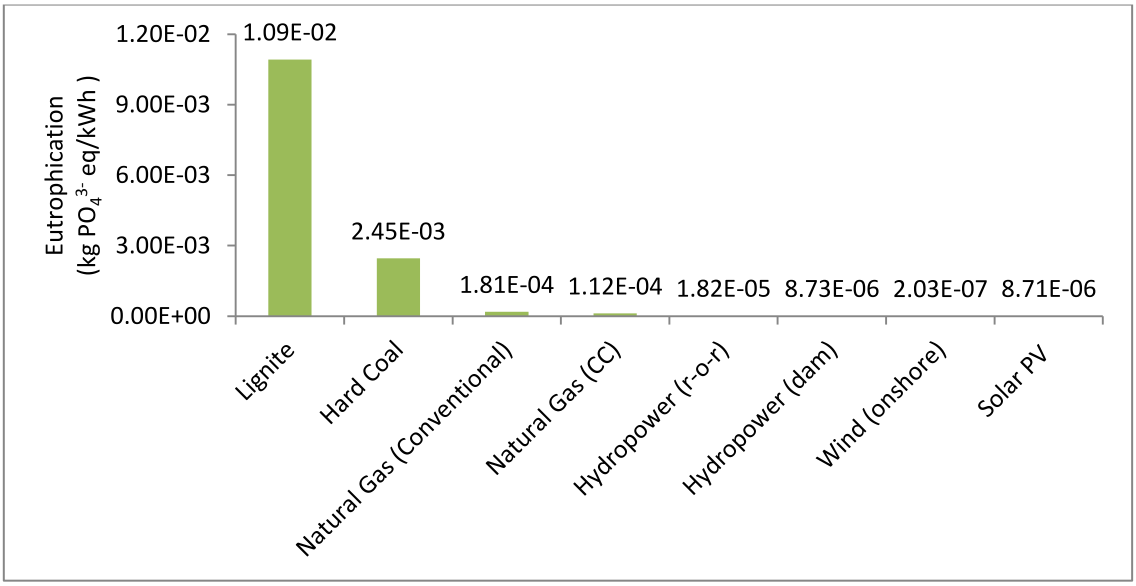


Figure 3.17 Eutrophication category scores for CML 2 Baseline 2000 method

Global warming (GWP100a) is concerned with the release of greenhouse gases to air. The results are given for time horizon 100 years. Fossil fuel power plant operation is the main contributor to greenhouse gas formation followed by fossil fuel utilization activities. As a result, fossil fuel technologies have higher scores for global warming category compared with renewable technologies (**Figure 3.18**).

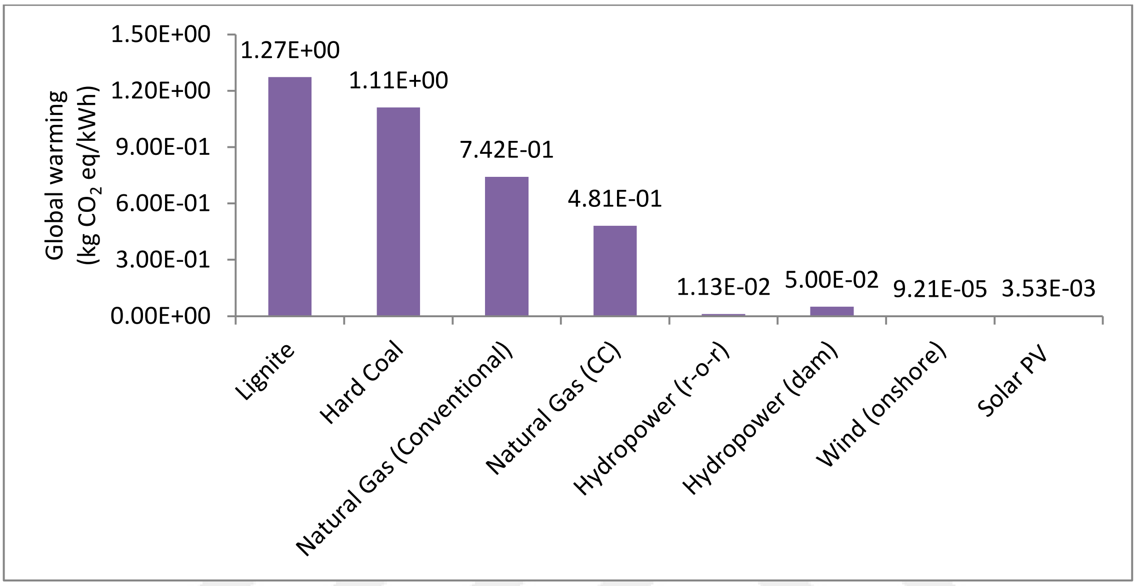


Figure 3.18 Global warming (GWP100a) category scores for CML 2 Baseline 2000 method

Ozone layer depletion indicates the ozone depletion potential of different gasses affecting animal health, human health, terrestrial and aquatic ecosystems, biochemical cycles and on materials. Ozone layer depletion is mainly caused by the extraction of gas and its long distance transport (Tagliaferri et al., 2017). The natural gas is transported via pipeline or in LNG form via freight. The highest scores are calculated for natural gas technologies followed by coal and then renewables. Even the scores are relatively close to each other, renewable technologies have the lowest values (**Figure 3.19**).

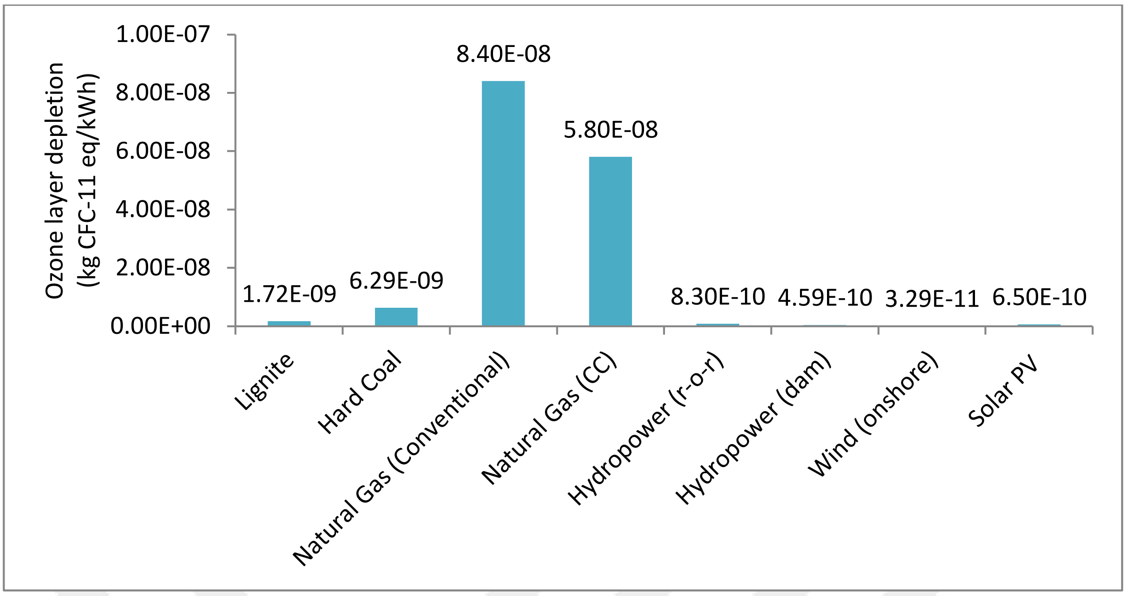


Figure 3.19 Ozone layer depletion category scores for CML 2 Baseline 2000 method

Human toxicity concerns the effects of toxic substances on the human environment especially emissions of heavy metals during the operation of power plants. Lignite and hard coal have the highest scores followed by natural gas and hydropower technologies. Renewable energy technologies wind and solar PV have lower values for this category (**Figure 3.20**).

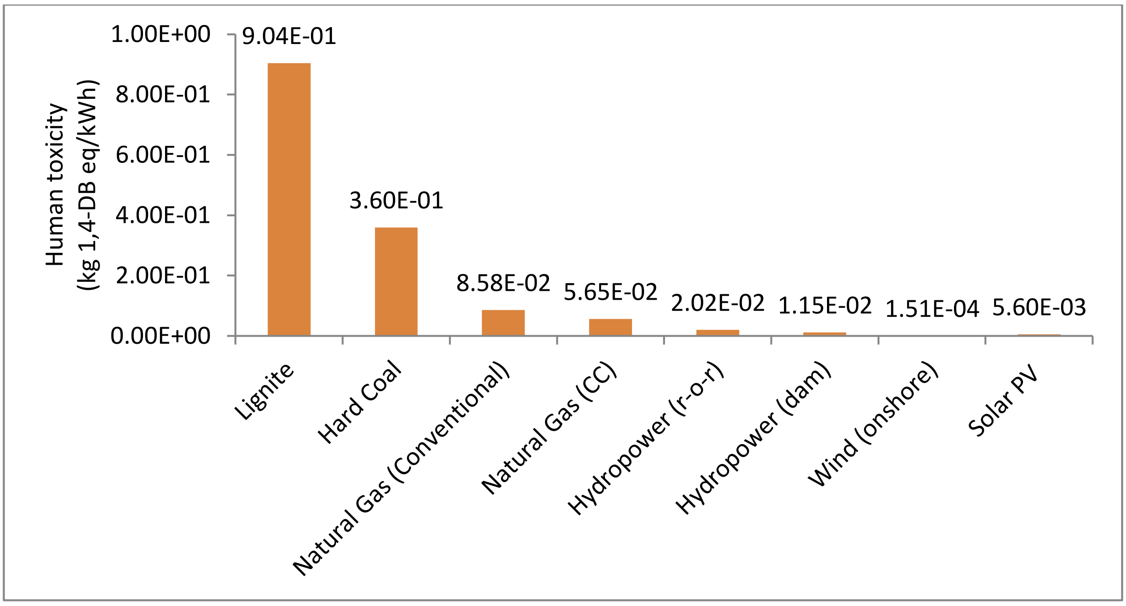


Figure 3.20 Human toxicity category scores for CML 2 Baseline 2000 method

Fresh water aquatic ecotoxicity refers to the impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water and soil especially due to the operation of power plants. Lignite and hard coal have the highest scores for this category. Natural gas and renewable energy technologies have relatively low scores (**Figure 3.21**).

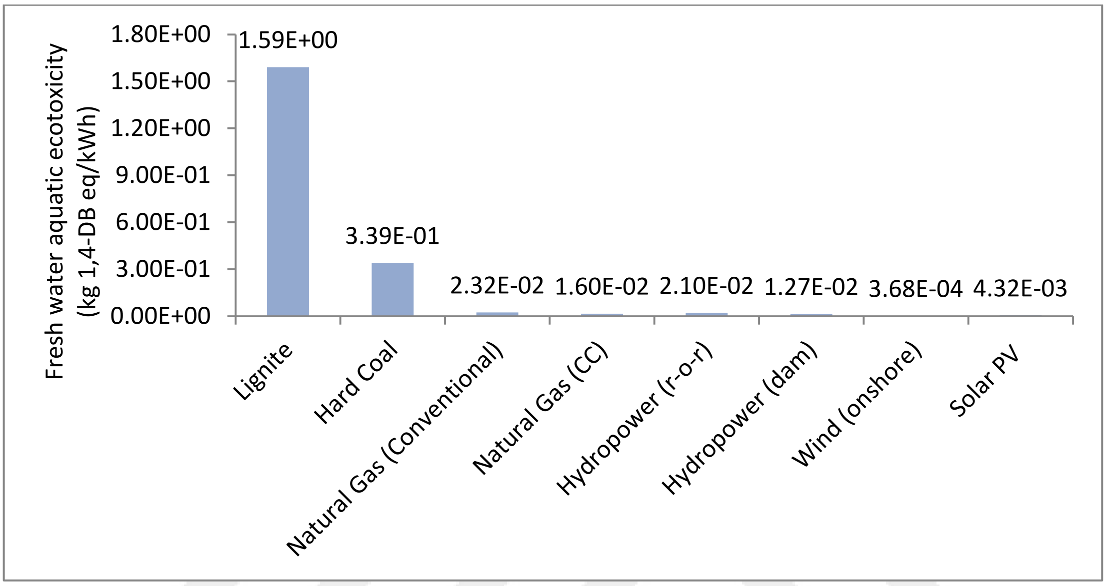


Figure 3.21 Fresh water aquatic ecotoxicity category scores for CML 2 Baseline 2000 method

Marine aquatic ecotoxicity refers to the impacts of toxic substances on marine ecosystems, as a result of emissions of toxic substances to air, water and soil especially due to the operation of power plants. Similar to freshwater ecotoxicity results, lignite and hard coal technologies have very high scores compared to other technologies while renewables have lower scores (**Figure 3.22**).

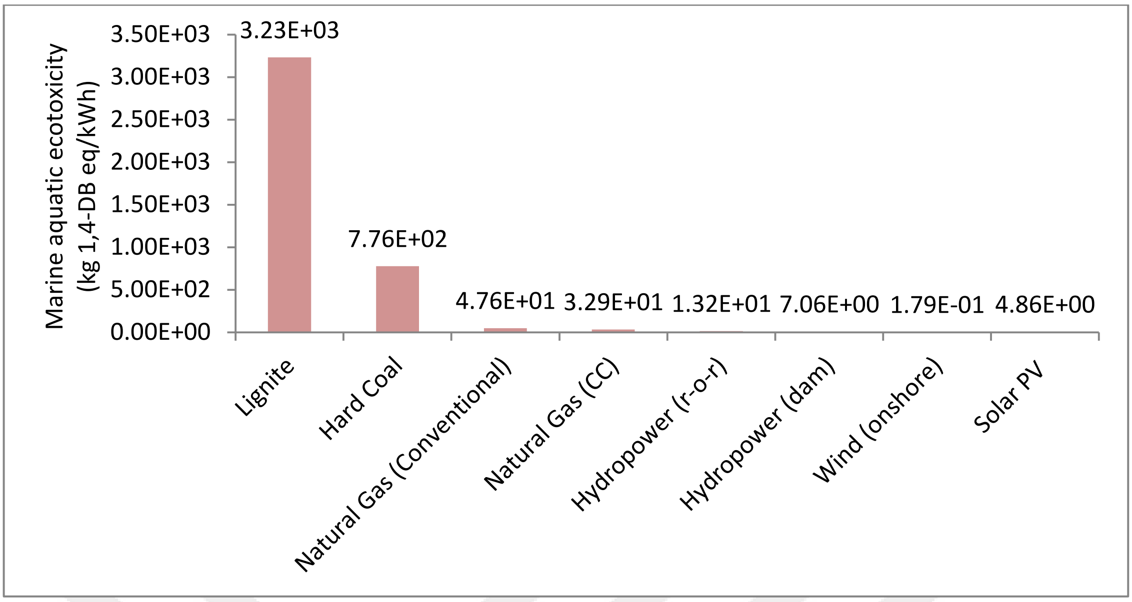


Figure 3.22 Marine aquatic ecotoxicity category scores for CML 2 Baseline 2000 method

Terrestrial ecotoxicity refers to impacts of toxic substances on terrestrial ecosystems, as a result of emissions of toxic substances to air, water and soil especially emissions of heavy metals during the operation of power plants. Similar to human toxicity results, lignite, hard coal and natural gas technologies are the main contributor to this indicator while wind technology has the lowest score (**Figure 3.23**).

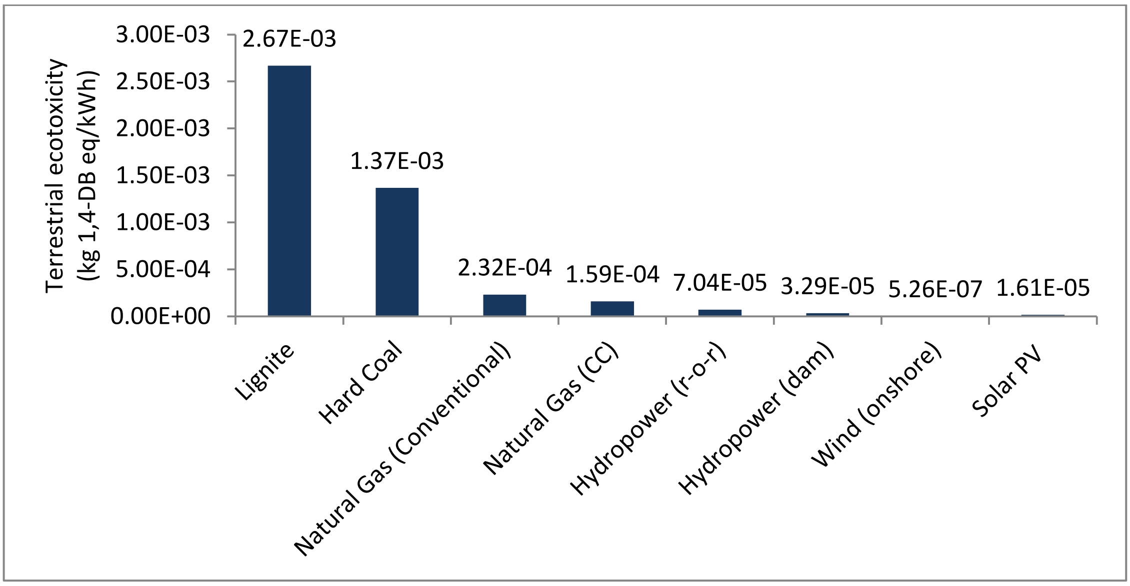


Figure 3.23 Terrestrial ecotoxicity category scores for CML 2 Baseline 2000 method

Photochemical oxidation is the formation of reactive substances (especially ozone) which threaten the human health and ecosystems and which may also damage crops. This impact is mainly caused from extraction and operation of fossil fuels. Lignite has the highest impact score followed by hard coal and natural gas technologies. Compared to fossil fuels, renewable technologies have lower values (**Figure 3.24**).

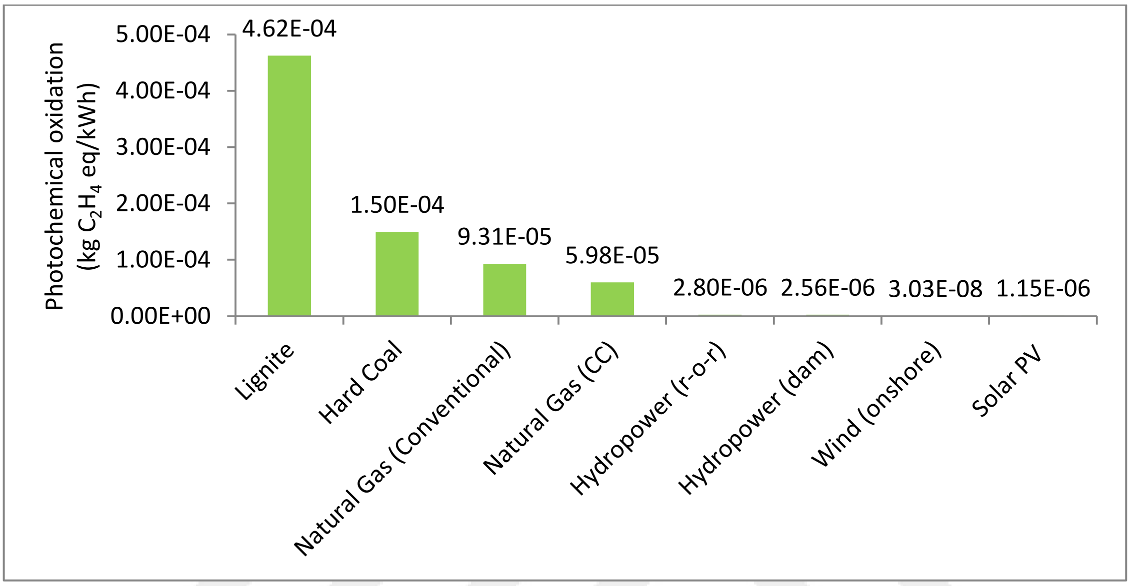


Figure 3.24 Photochemical oxidation category scores for CML 2 Baseline 2000 method

3.1.3.5 ReCiPe (H) midpoint

ReCiPe midpoint method is applied with hierarchist (H) perspective since it is based on the most common policy principles regarding time-frame and average weighting. Also, this perspective is widely accepted for scientific and political studies. The results are expressed in eighteen categories as explained below (See Appendix A6).

Climate change scores for lignite and hard coal have the highest values followed by natural gas technologies. Fossil fuels are the main contributor to climate change due to their high carbon content. Compared to fossil fuels, renewable energy technologies have fairly lower scores as seen in **Figure 3.25**.

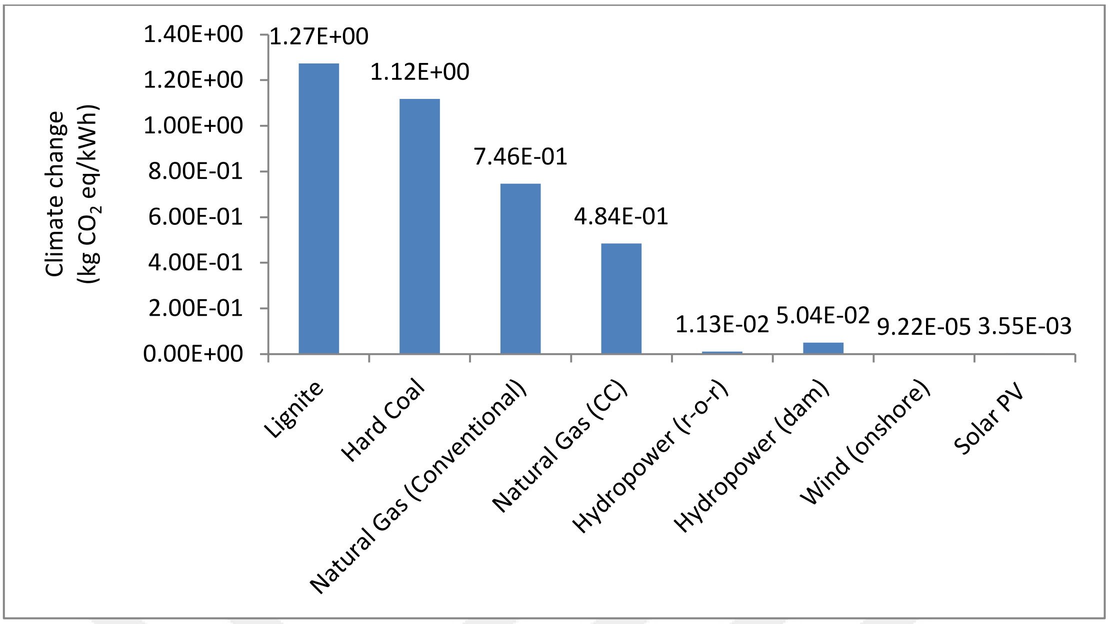


Figure 3.25 Climate change category scores for ReCiPe (H) midpoint method

Ozone depletion scores have the highest value for natural gas technologies due to its extraction and long distance transport. Lignite and hard coal technologies have relatively lower scores compared to natural gas while renewable technologies have the lowest impacts (**Figure 3.26**).

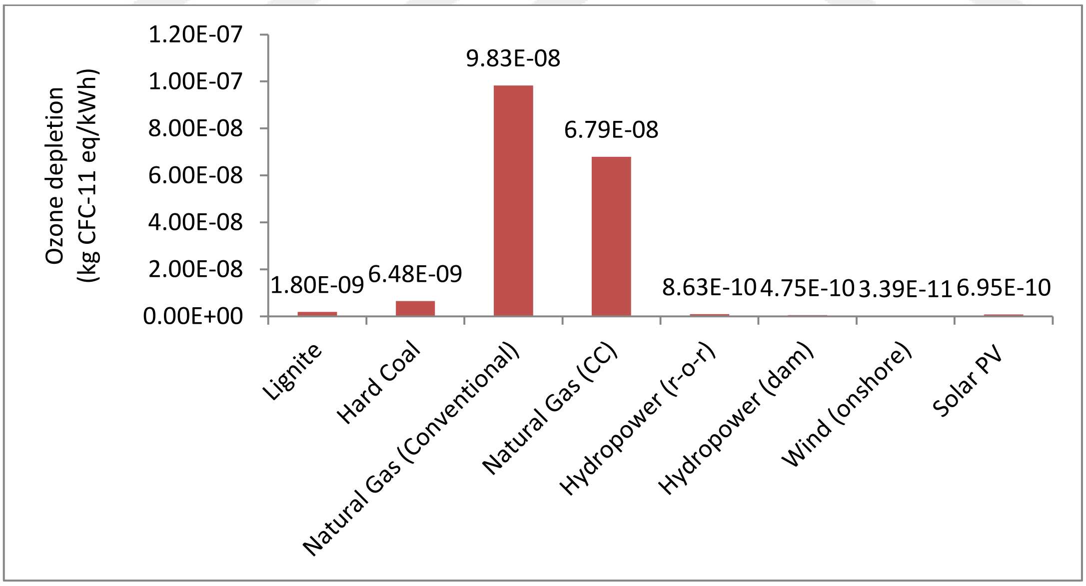


Figure 3.26 Ozone depletion category scores for ReCiPe (H) midpoint method

Terrestrial acidification scores show that lignite technology has the highest impact scores followed by hard coal, this score is mainly caused by their high sulphur content. Natural gas technology scores moderately lower for this category where renewable technologies have the lowest score (**Figure 3.27**).

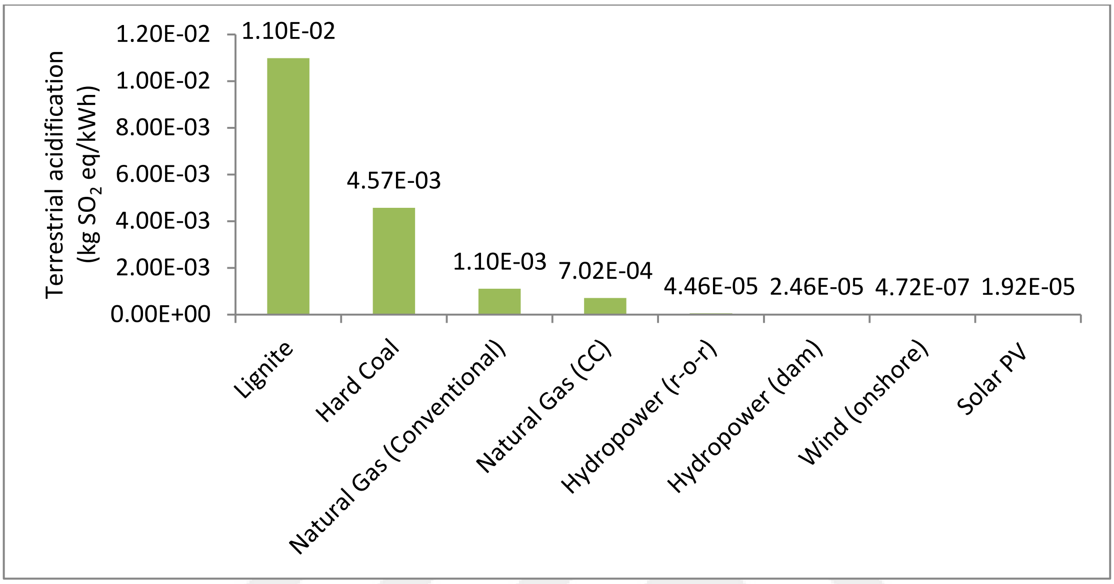


Figure 3.27 Terrestrial acidification category scores for ReCiPe (H) midpoint method

Freshwater eutrophication impact scores have the highest values for lignite and then hard coal technologies resulting from power plant operation. Natural gas and renewable energy technologies have quite lower scores for this impact category (**Figure 3.28**).

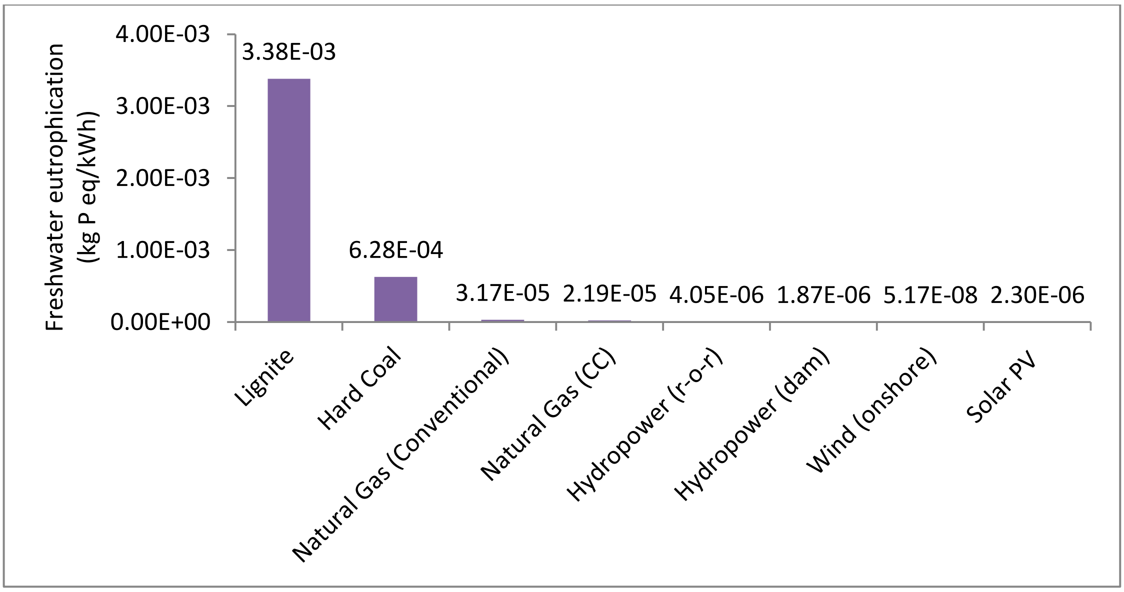


Figure 3.28 Freshwater eutrophication category scores for ReCiPe (H) midpoint method

Marine eutrophication scores show similar trend with freshwater eutrophication category scores. Lignite and hard coal technologies have the highest scores. Natural gas and renewable energy technologies have quite lower scores for this impact category (**Figure 3.29**).

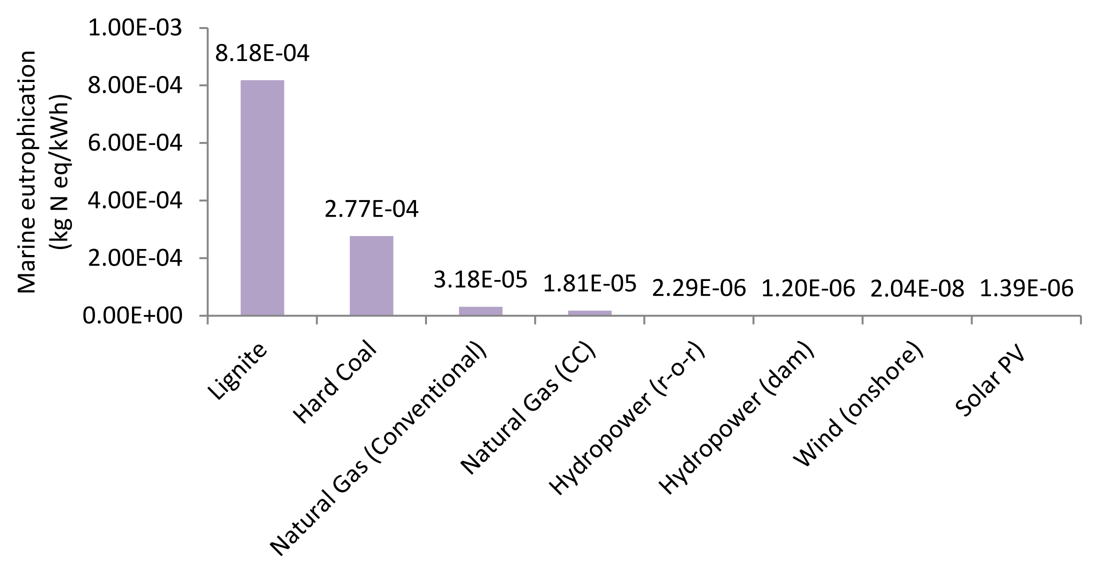


Figure 3.29 Marine eutrophication category scores for ReCiPe (H) midpoint method

Human toxicity impact scores have the highest value for lignite and hard coal technologies due to the emissions of heavy metals to air during power plant operation. Natural gas and renewable technologies have comparatively lower scores for this impact category (**Figure 3.30**).

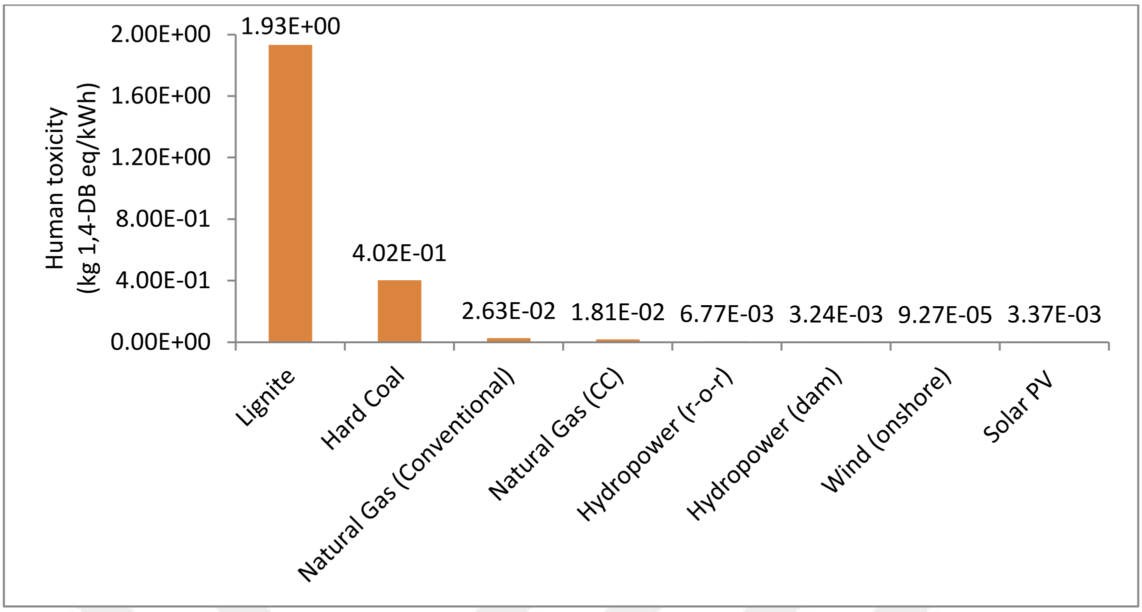


Figure 3.30 Human toxicity category scores for ReCiPe (H) midpoint method

Photochemical oxidant formation scores have the highest values for hard coal technology followed by lignite due to power plant operation – especially as a result of the combustion process. Natural gas has moderate scores while the renewables have the lowest impacts (**Figure 3.31**).

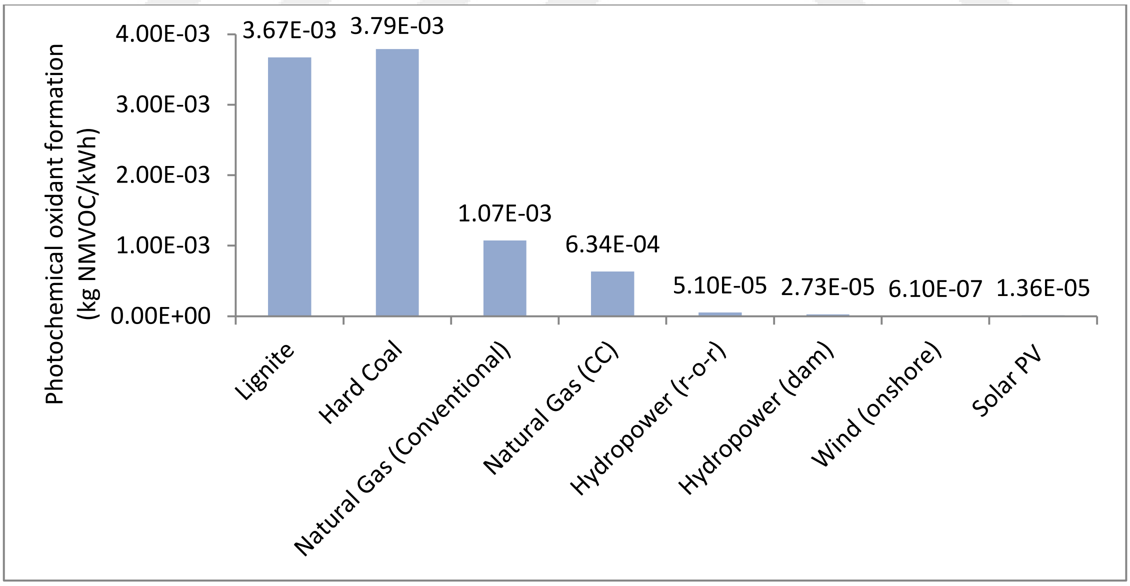


Figure 3.31 Photochemical oxidant formation category scores for ReCiPe (H) midpoint method

Particulate matter formation scores are based on the amount of fine particulate matters with a diameter of less than 10 μm (PM10). The particulate matter formation scores have the highest value for lignite technology due to its high ash content. All of the generation types except lignite have rather lower values while wind technology has the lowest impact score (**Figure 3.32**).

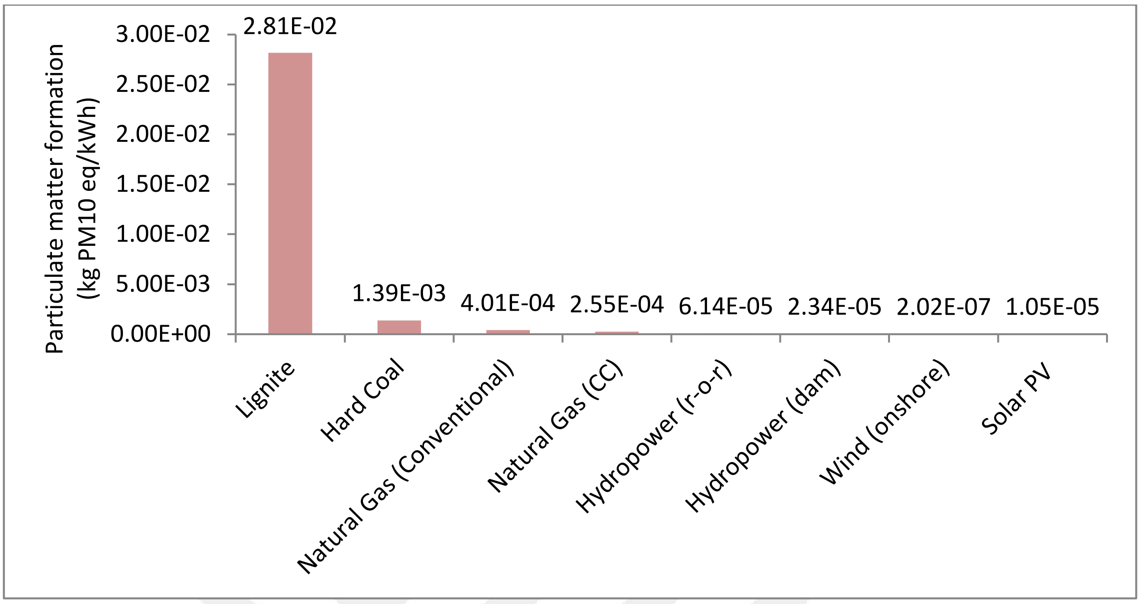


Figure 3.32 Particulate matter formation category scores for ReCiPe (H) midpoint method

Terrestrial ecotoxicity scores have the highest value for hard coal technologies due to the heavy metal emissions during power plant operation. The scores are followed by lignite, conventional natural gas, solar PV, combined cycle natural gas, run-of-river hydropower, hydropower with dam, and wind technologies (**Figure 3.33**).

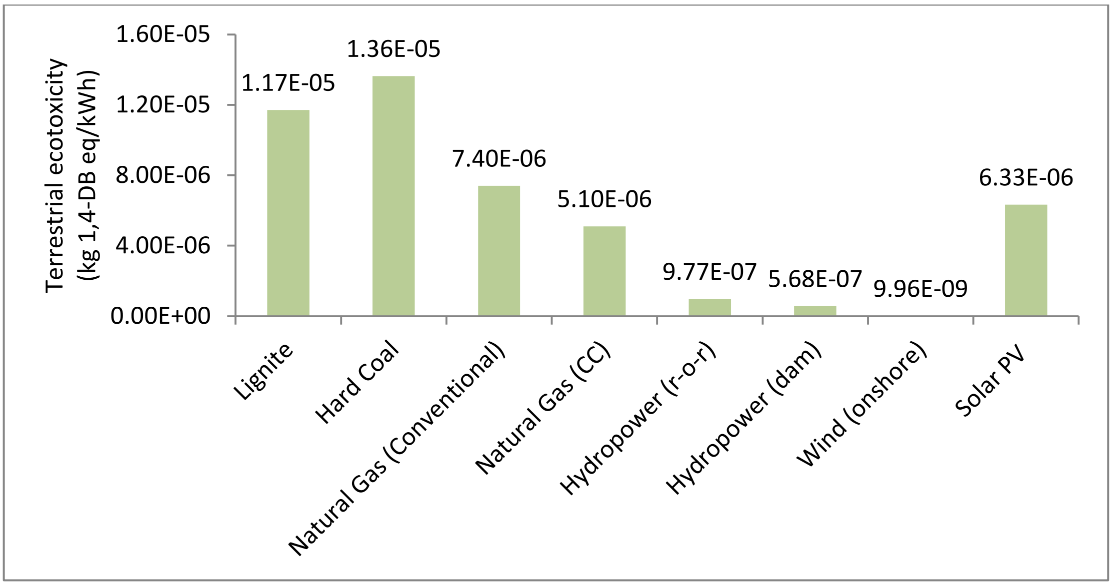


Figure 3.33 Terrestrial ecotoxicity category scores for ReCiPe (H) midpoint method

Freshwater ecotoxicity scores have the highest value for lignite technologies due to heavy metal emissions during power plant operation. Other technology scores are close to each other and ranked as hard coal, hydropower, natural gas and other renewable technologies (**Figure 3.34**).

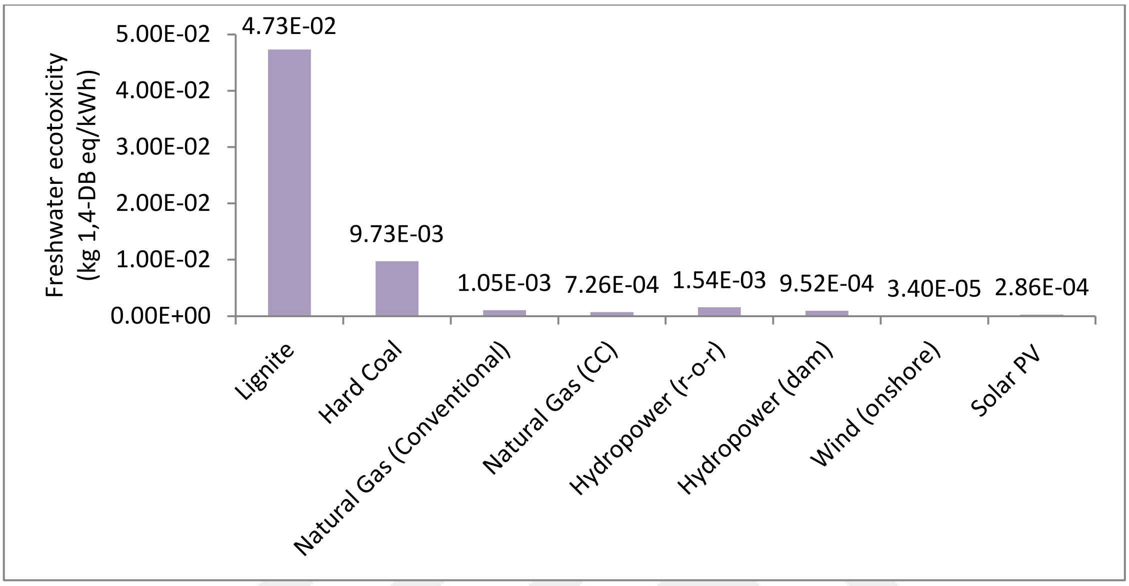


Figure 3.34 Freshwater ecotoxicity category scores for ReCiPe (H) midpoint method

Marine ecotoxicity scores show similar tendency with freshwater ecotoxicity scores. Lignite technology has the highest toxicity followed by hard coal, hydropower, natural gas, and other renewable technologies (**Figure 3.35**).

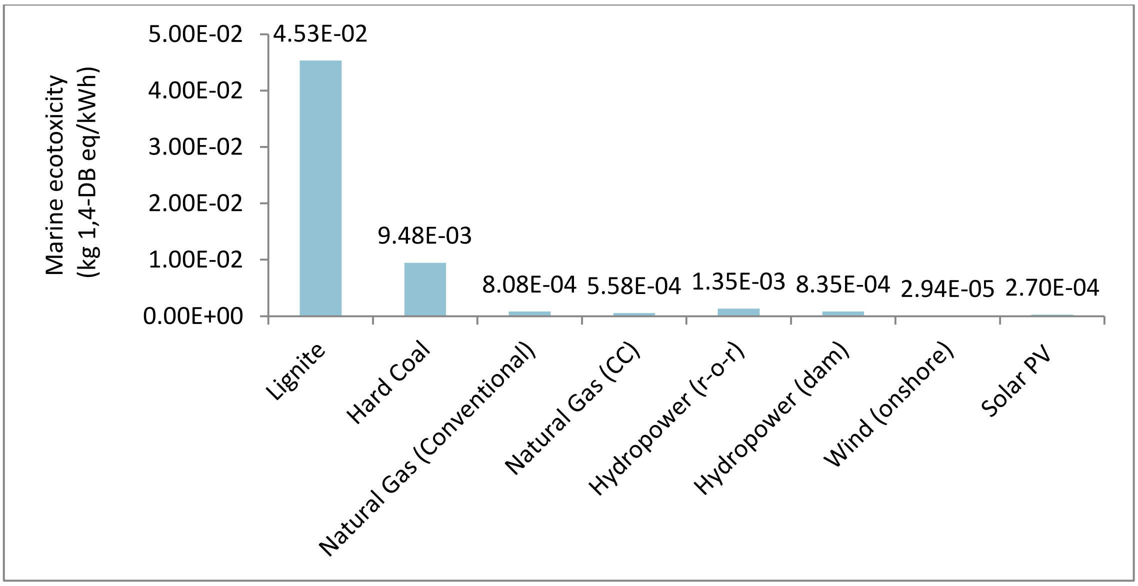


Figure 3.35 Marine ecotoxicity category scores for ReCiPe (H) midpoint method

Ionising radiation scores have the highest values for fossil fuel technologies due to the release of radioactive material to the environment. The ranking is as following: conventional natural gas, combined cycle natural gas, hard coal, lignite, hydropower, solar PV, and wind (**Figure 3.36**).

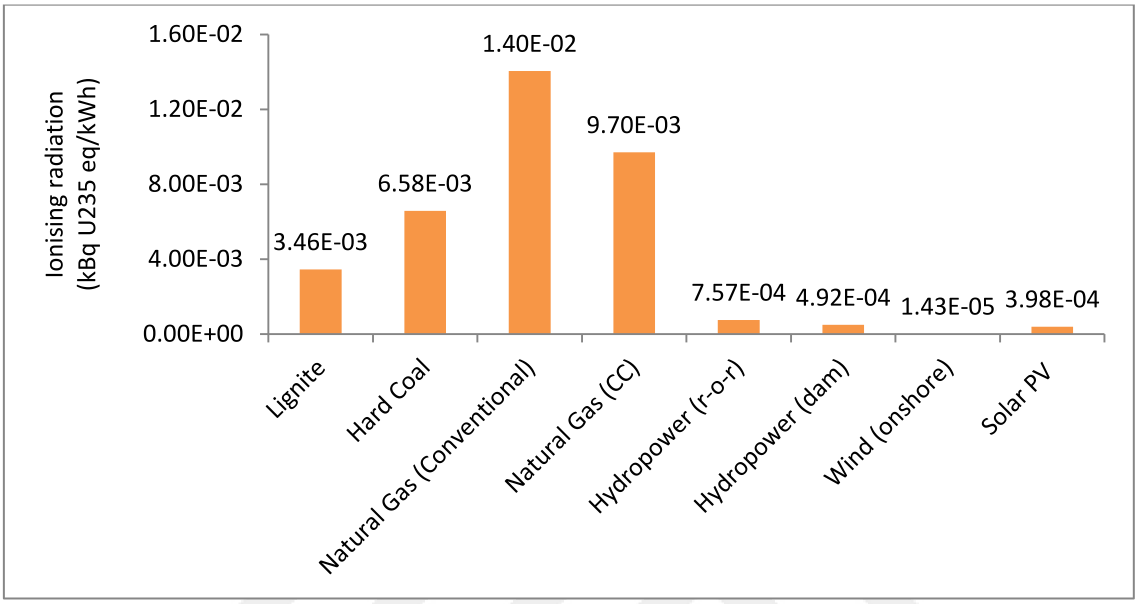


Figure 3.36 Ionising radiation category scores for ReCiPe (H) midpoint method

Agricultural land occupation scores have the highest value for hard coal technology due to the mining and power plant construction activities. Lignite, conventional natural gas, run-of-river hydropower, and combined cycle natural gas technologies are the followings. Renewable energy technologies have relatively lower scores (**Figure 3.37**).

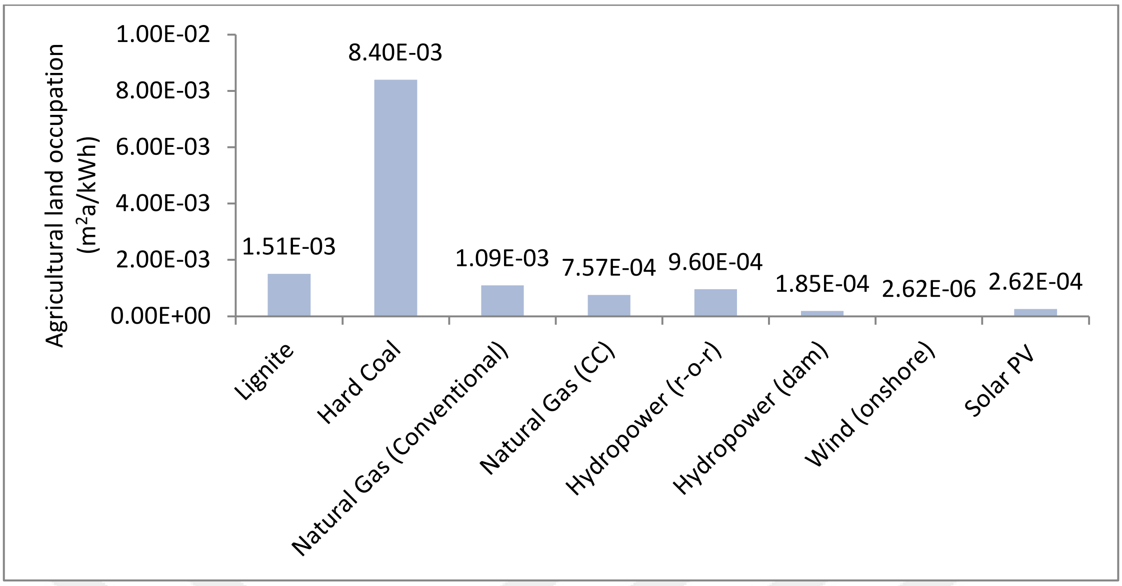


Figure 3.37 Agricultural land occupation category scores for ReCiPe (H) midpoint method

Urban land occupation scores show similar trend with agricultural land occupation scores and the highest value for hard coal technologies is followed by lignite and solar PV. Natural gas, hydropower and wind technologies have lower scores (**Figure 3.38**).

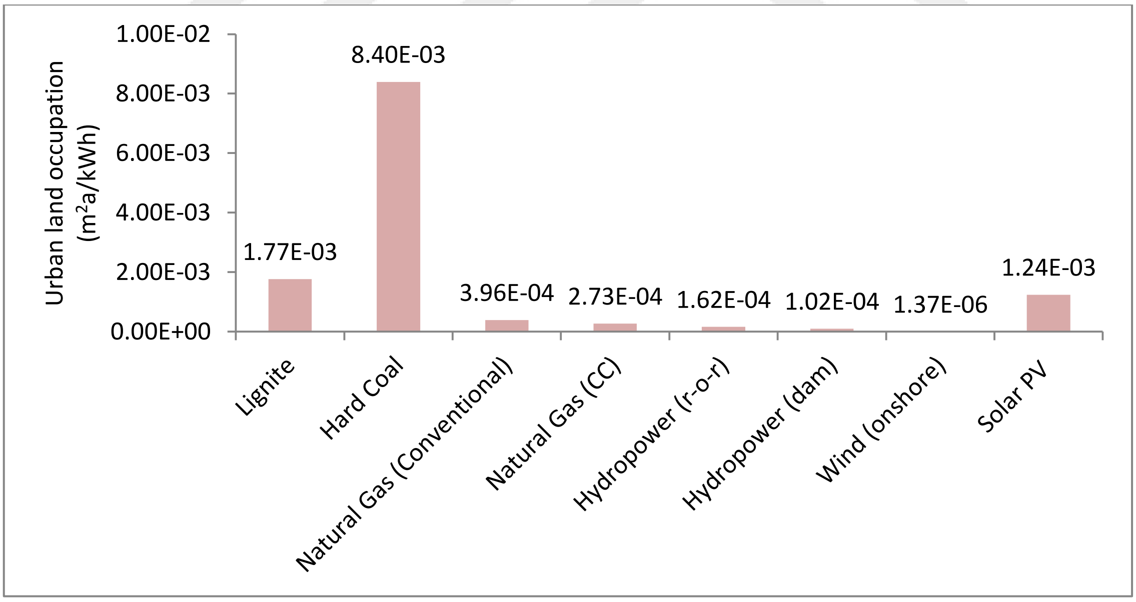


Figure 3.38 Urban land occupation category scores for ReCiPe (H) midpoint method

Natural land transformation scores have the highest values for conventional natural gas technology and hydropower with dam due to fuel extraction and power plant construction. The ranking is followed by combined cycle natural gas, hard coal, lignite, and renewable technologies (**Figure 3.39**).

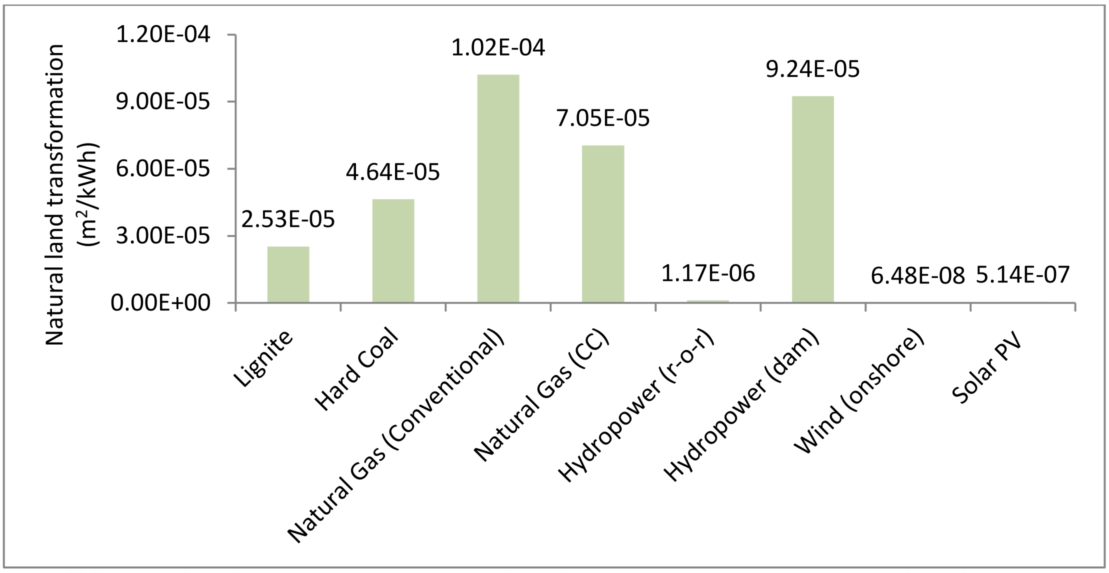


Figure 3.39 Natural land transformation category scores for ReCiPe (H) midpoint method

Water depletion scores have the highest value for hydropower with dam technologies and the other alternatives have significantly lower scores (**Figure 3.40**). Natural gas combine cycle technologies have negative scores implying a decrease in the water consumption and positive effect on the environment. This is mainly due to the cooling activities during LNG processing.

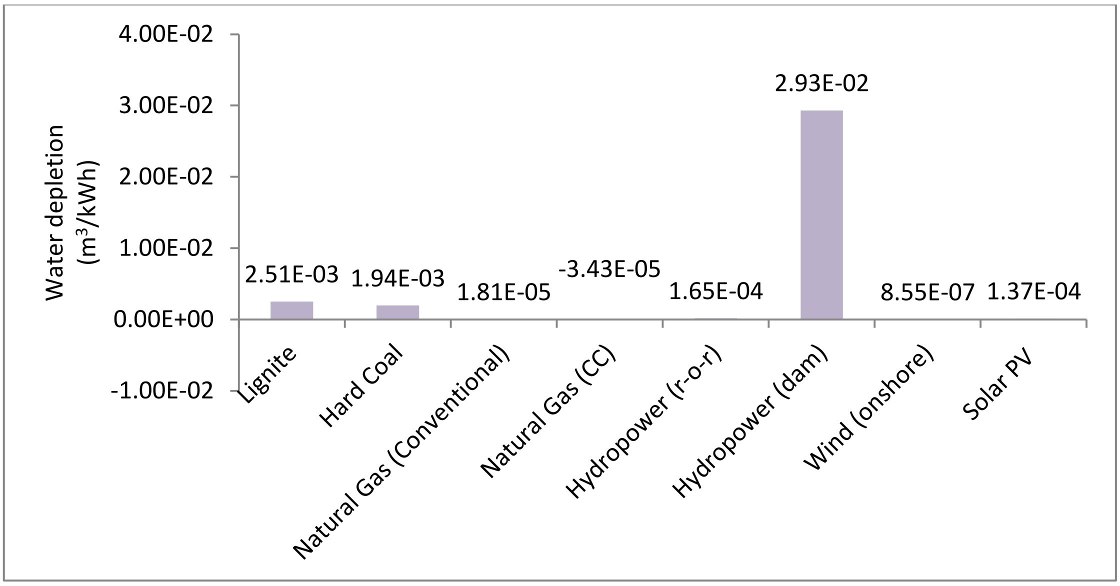


Figure 3.40 Water depletion category scores for ReCiPe (H) midpoint method

Metal depletion scores show different characteristics than the other category results. Run-of-river hydropower has the highest value followed by conventional natural gas technology. The ranking is listed as combined cycle natural gas, hydropower with dam, hard coal, lignite, solar PV and wind technology (**Figure 3.41**).

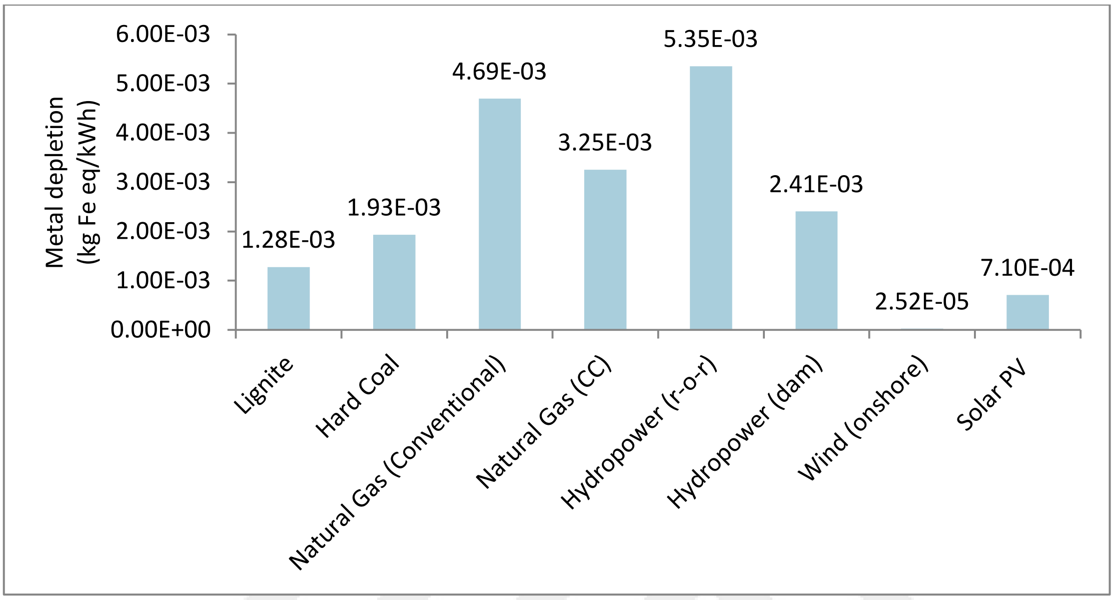


Figure 3.41 Metal depletion category scores for ReCiPe (H) midpoint method

Fossil depletion scores are higher for the fossil fuel technologies as expected. Renewable energy technologies have reasonably lower scores for this category (**Figure 3.42**).

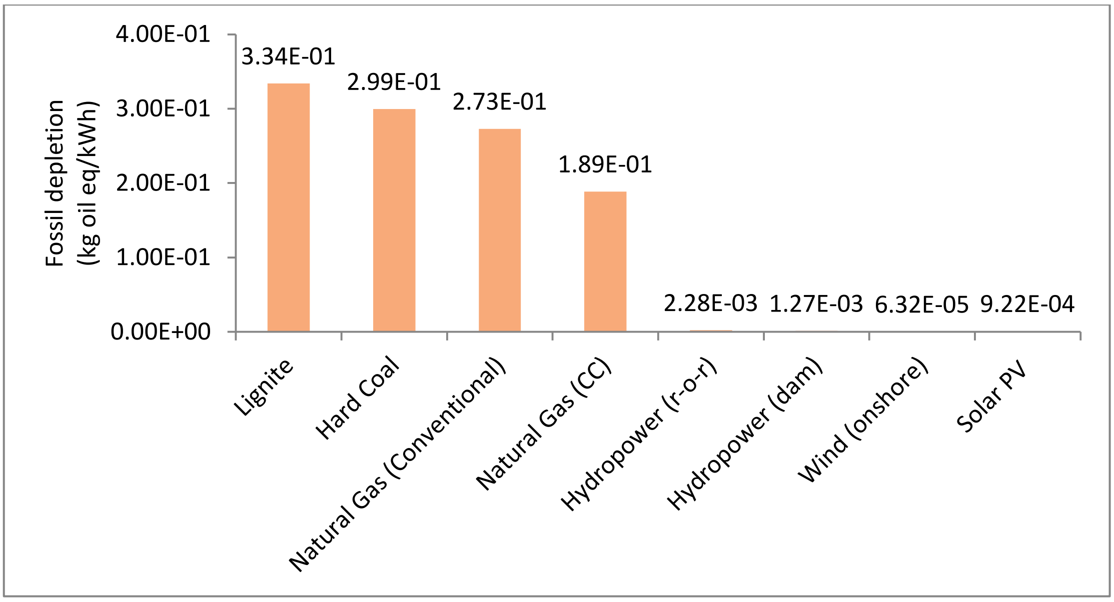


Figure 3.42 Fossil depletion category scores for ReCiPe (H) midpoint method

3.1.3.6 ReCiPe (H) endpoint

ReCiPe (H) endpoint method aims to draw a conclusion from the numerous midpoint categories into a representative single score. First, midpoint impact categories are multiplied with damage factors and combined into three endpoint categories: human health, ecosystems and resource surplus costs. Then, three endpoint categories are normalized, weighted, and aggregated into a single score as previously shown in **Figure 2.4**.

Three damage category scores are given in the Appendix A7. Also, the contribution of each generation technology to three damage categories is given in **Figure 3.43**. *Human health* damage category score is 11.3 GPt and mainly resulted from lignite and hard coal technologies. *Ecosystems* category score is 2.82 GPt and resulted from lignite, hard coal and natural gas technologies. Also hydropower with dam technology has minor contribution to the damage category score. *Resource surplus cost* category score is 5.16 GPt and resulted from natural gas technologies with hard coal and lignite. In short, fossil fuel technologies are the main contributors to each damage category having very high scores compared to renewable technologies.

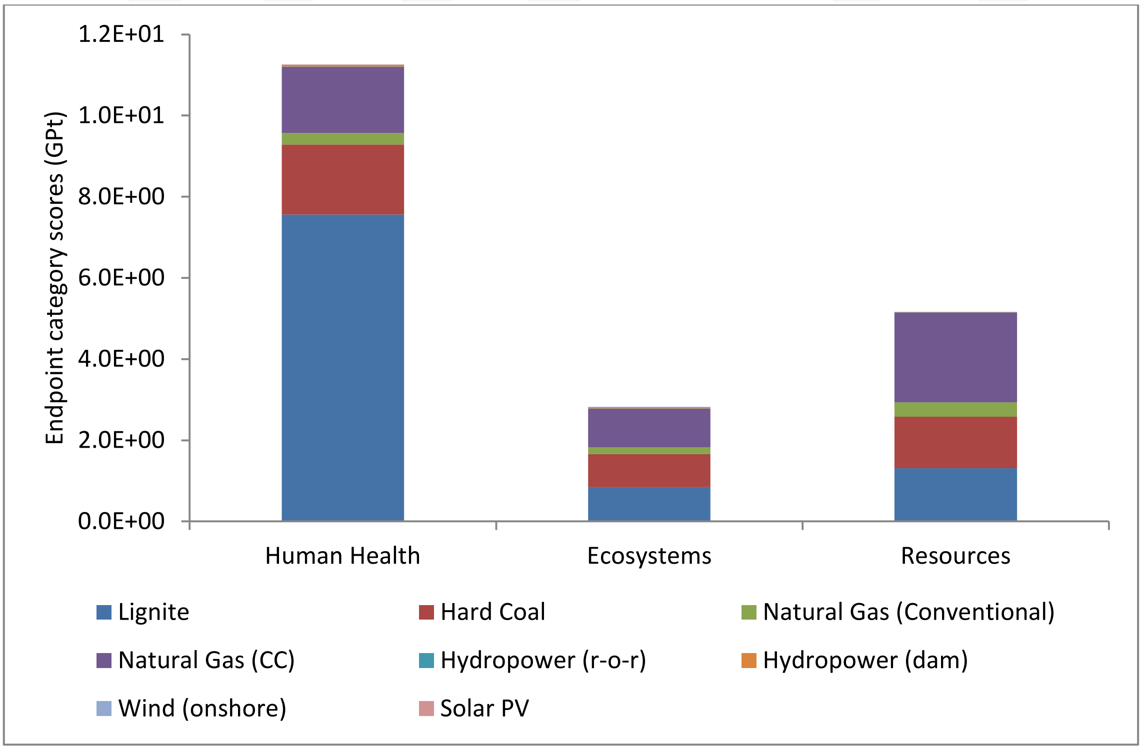


Figure 3.43 Damage category contribution scores for ReCiPe (H) endpoint method

3.1.4 Estimation of the future projections

First of all, future scenarios are investigated for their consistency with the ongoing electricity generation activities. 2015, 2016 and 2017 total generation values are compared with the three future scenarios. The official plans scenario has a lower overlapping score for these three years than business-as-usual and renewables development pathway scenarios as correlation factors are 0.92 and 0.99 for official plans and both business-as-usual and renewables development pathway scenarios, respectively (**Figure 3.44**). The correlation factor indicates that the projections are more realistic for BAU and RDP scenarios compared to OP scenario.

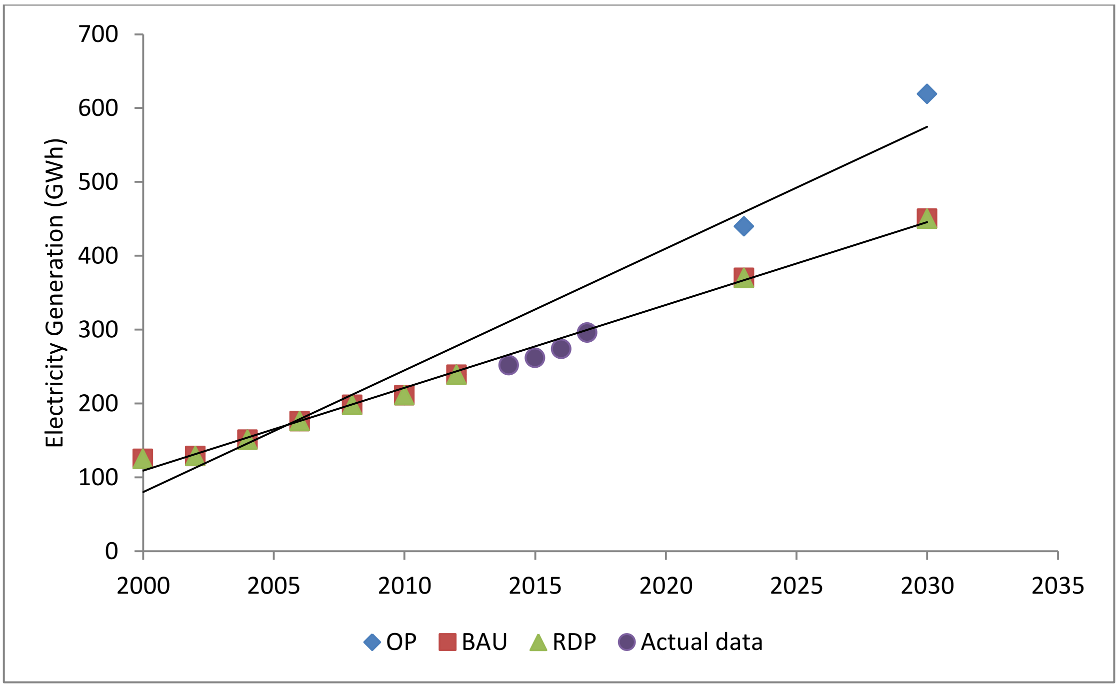


Figure 3.44 Comparison of future scenarios with the actual generation data

After future projection investigation, comparisons of future scenarios with 2014 are performed. The results are expressed in total impact generated for total electricity generated in the studied year.

3.1.4.1 IPCC 2013 global warming potential (GWP 100a)

Global warming potential scores of the current situation and future scenarios are depicted in **Figure 3.45**. Carbon-based emissions are the main contributors to global warming; as the share of fossil fuel technologies increases, carbon-based emissions tend to increase, too. GWP scores for BAU and OP scenarios have increasing values for 2023 and 2030 projections (See Appendix A8). As seen in the results, GWP scores are kept close to 2014 levels only if the RDP strategy is put into practice.

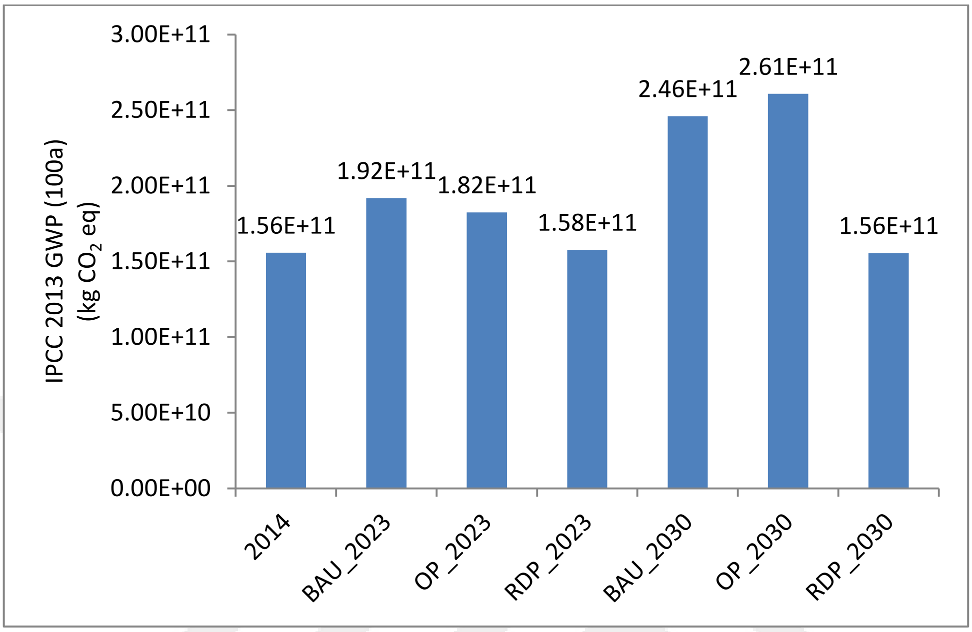


Figure 3.45 Comparison of future scenarios with 2014 via PCC 2013 global warming potential (GWP 100a) method

3.1.4.2 Cumulative energy demand (CED)

Cumulative energy demand scores of the current situation and future scenarios are tabulated in Appendix A9. According to the results, *Non-renewable, fossil CED* scores show increasing trend for BAU and OP scenarios even the scenario scores for 2023 have lower scores than 2014. RDP scenario shows a decline from 2014 to 2030 due to the decreasing share of fossil fuels. Non-renewable fossil CED can only be kept in 2014 levels if RDP is employed (**Figure 3.46**).

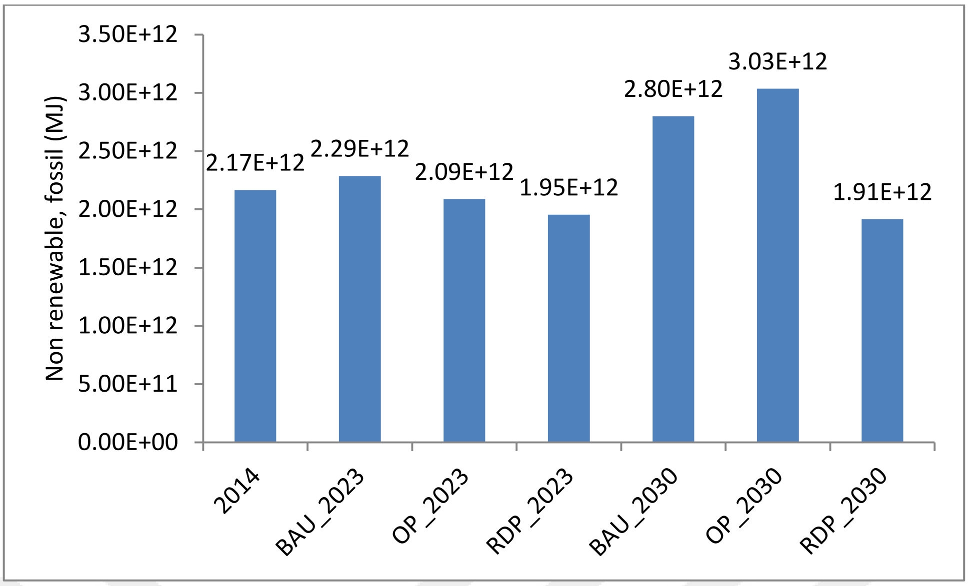


Figure 3.46 Comparison of non-renewable, fossil CED scores for future scenarios

Non-renewable, nuclear CED has higher scores for OP since it proposes a higher level of nuclear share in the electricity generation mix. As mentioned before, OP scenario is based on overestimated assumptions and current generation trend confirms the predictions for BAU and RDP alternatives. According to the nuclear share in the generation mix, CED scores are increasing in time (**Figure 3.47**).

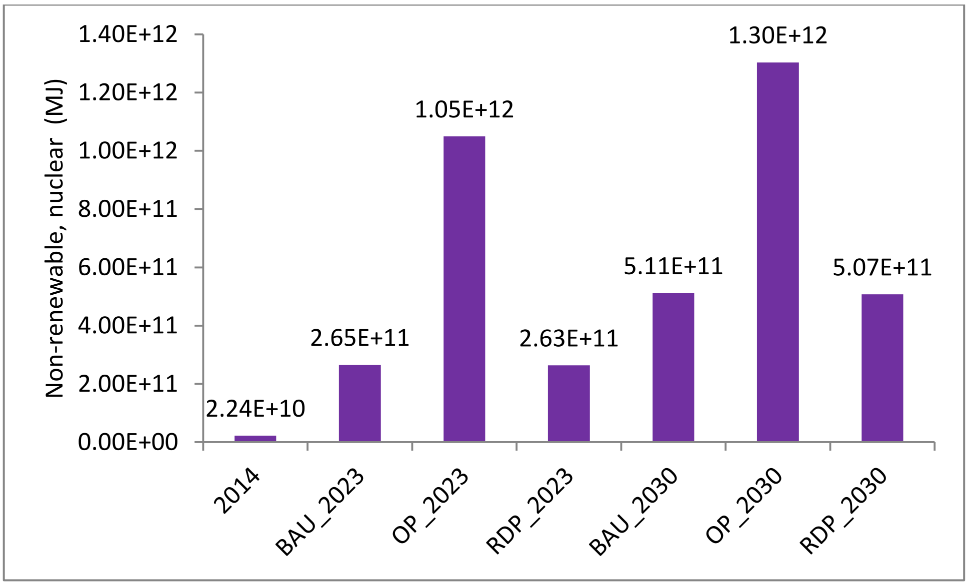


Figure 3.47 Comparison of non-renewable, nuclear CED scores for future scenarios

Renewable wind and solar CED scores increase in all future scenarios since the renewable share is expected to rise in all cases. Even the highest score is achieved for OP scenario; its target is out of reach according to the current generation levels. BAU and RDP scenarios also propose higher share of renewable technologies, so their CED scores show a rising trend in time (**Figure 3.48**).

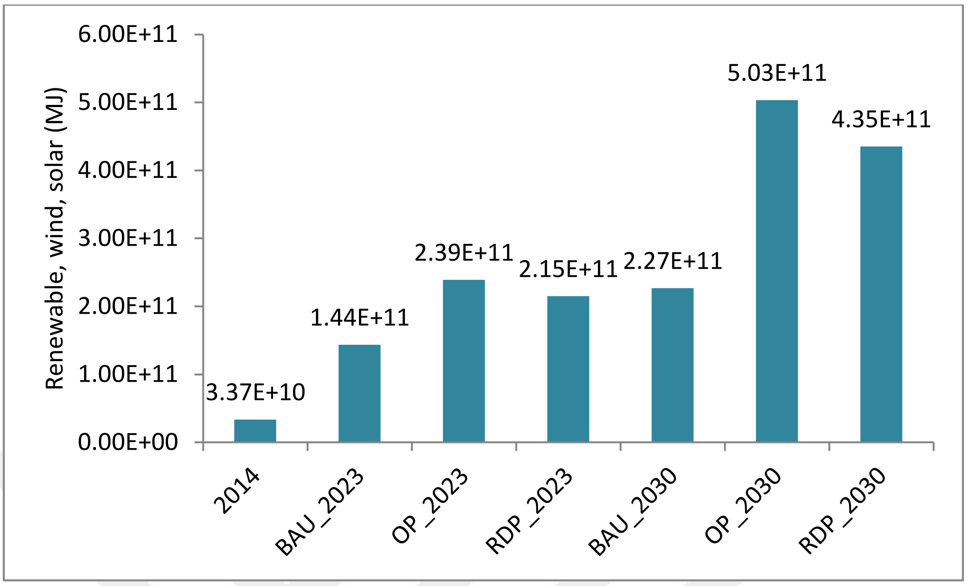


Figure 3.48 Comparison of renewable, wind, solar CED scores for future scenarios

Renewable, water CED also increases in all scenarios due to the expected shift to renewable energy technologies. All of the scenarios propose similar generation share in the future electricity mix. As a result, CED scores change in similar trends (**Figure 3.49**).

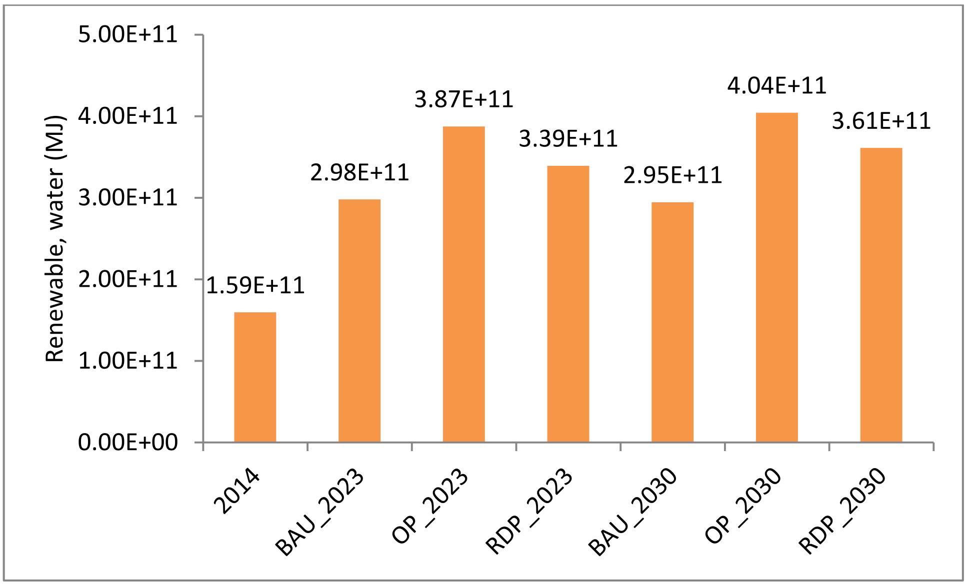


Figure 3.49 Comparison of renewable, water CED scores for future scenarios

3.1.4.3 Cumulative exergy demand (CExD)

Cumulative exergy demand scores of the current situation and future scenarios are tabulated in Appendix A10. *Non-renewable, fossil CExD* scores show an increasing trend for BAU and OP scenarios even OP scenario for 2023 has lower score than 2014. RDP scenario shows a decline from 2014 to 2030 due to the decreasing share of fossil fuels. Non-renewable fossil CExD can only be kept in 2014 levels if RDP is applied (**Figure 3.50**).

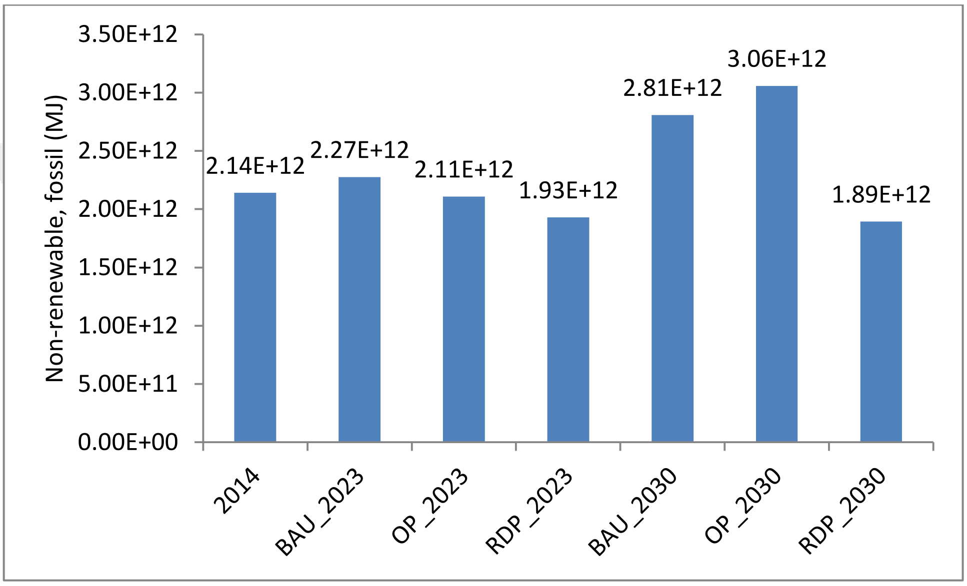


Figure 3.50 Comparison of non-renewable, fossil CExD scores for future scenarios

Non-renewable, nuclear CExD has higher scores for OP since it proposes a higher level of nuclear share in the electricity generation mix. As mentioned before, OP scenario is based on overestimated assumptions and current generation trend confirms the predictions for BAU and RDP alternatives. According to the nuclear share in the generation mix, CExD scores are increasing in time for both BAU and RDP scenarios (**Figure 3.51**).

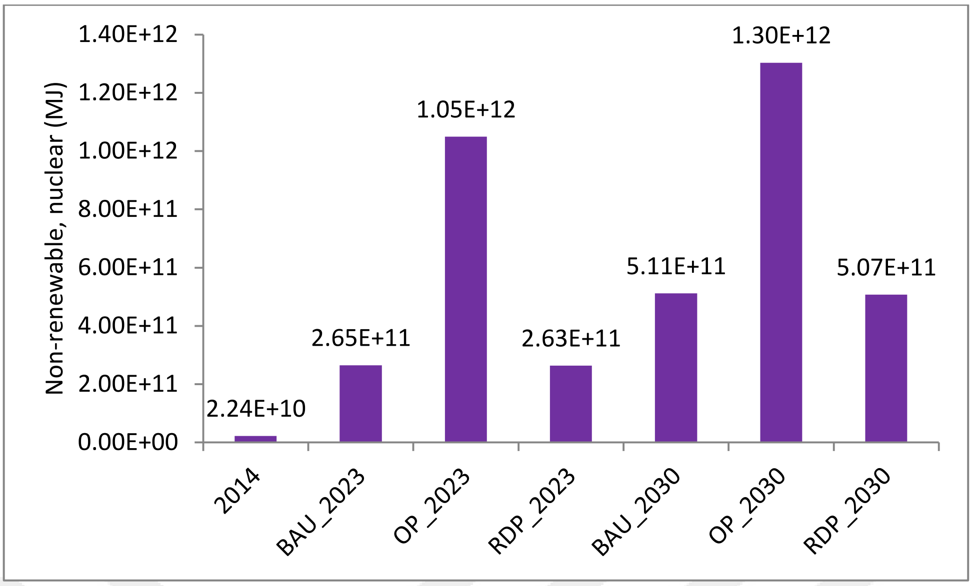


Figure 3.51 Comparison of non-renewable, nuclear CExD scores for future scenarios

Renewable, kinetic CExD has higher scores for OP projections since it proposes higher wind shares in the generation mix. However, all of the scenarios show increasing trend for future due to the increasing share of wind technology (**Figure 3.52**).

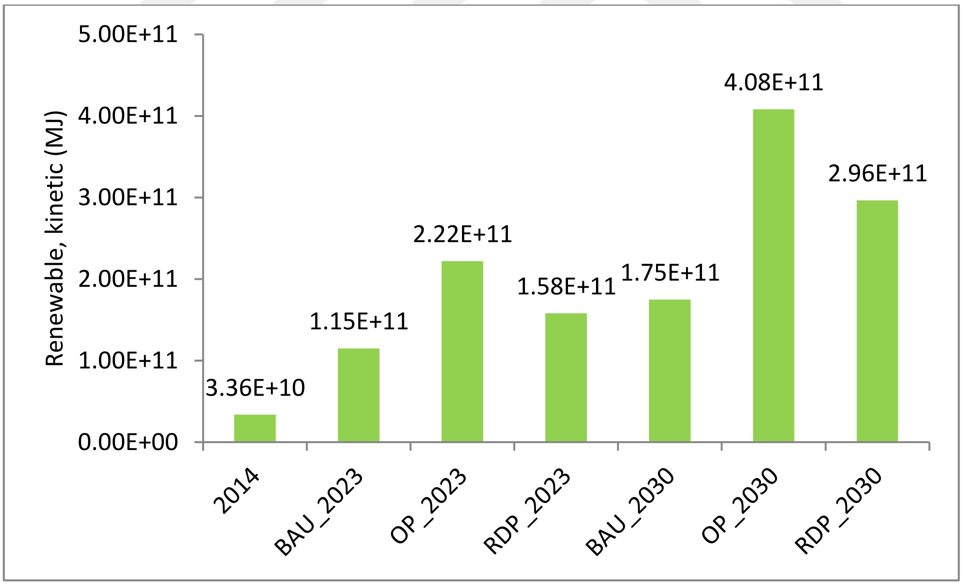


Figure 3.52 Comparison of renewable, kinetic CExD scores for future scenarios

Renewable, solar CExD has the highest scores for RDP projections since it proposes higher solar shares in the future generation mix. However, all of the scenarios show increasing trend for future due to the increasing share of solar technology (**Figure 3.53**).

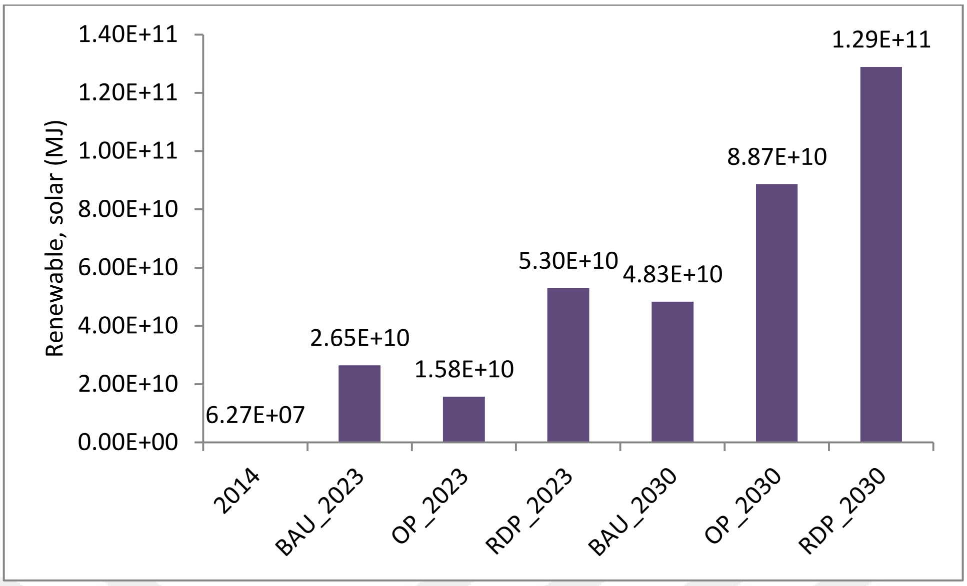


Figure 3.53 Comparison of renewable, solar CExD scores for future scenarios

Renewable, potential CExD scores are mainly resulted from hydropower technologies. All of the scenarios propose that CExD scores almost remain the same for 2023 and 2030 projections in the scenario basis, yet they are higher than 2014 levels (**Figure 3.54**).

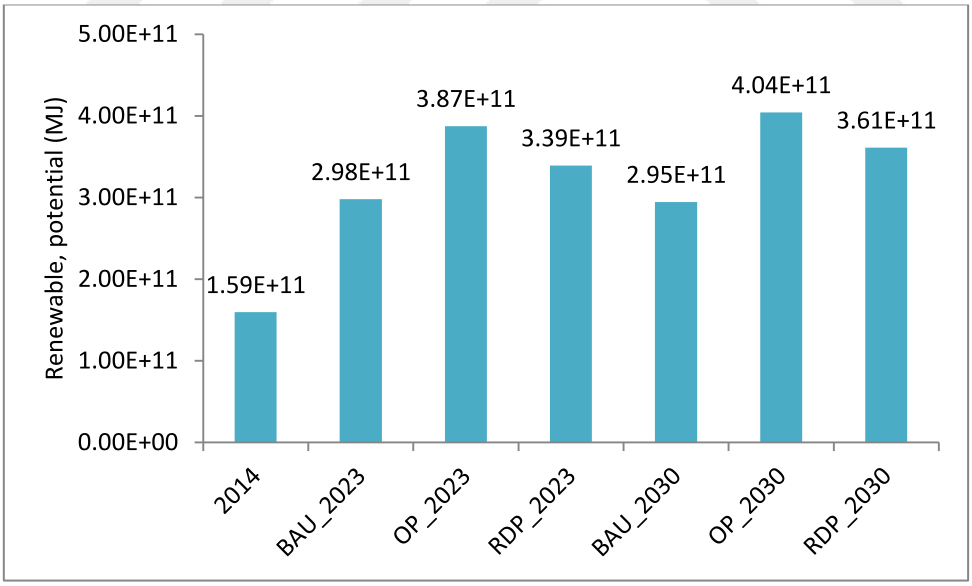


Figure 3.54 Comparison of renewable, potential CExD scores for future scenarios

Non-renewable, primary CExD scores have the highest value for 2014 case since natural gas share in this year is higher from the future scenarios. All of the scenarios propose a decline in the natural gas share in the generation mix for 2023 due to its financial, environmental and socio-economic drawbacks. Even if the natural gas shares are expected to decrease until 2030, CExD have increasing values due to the increase in the total electricity generation (**Figure 3.55**).

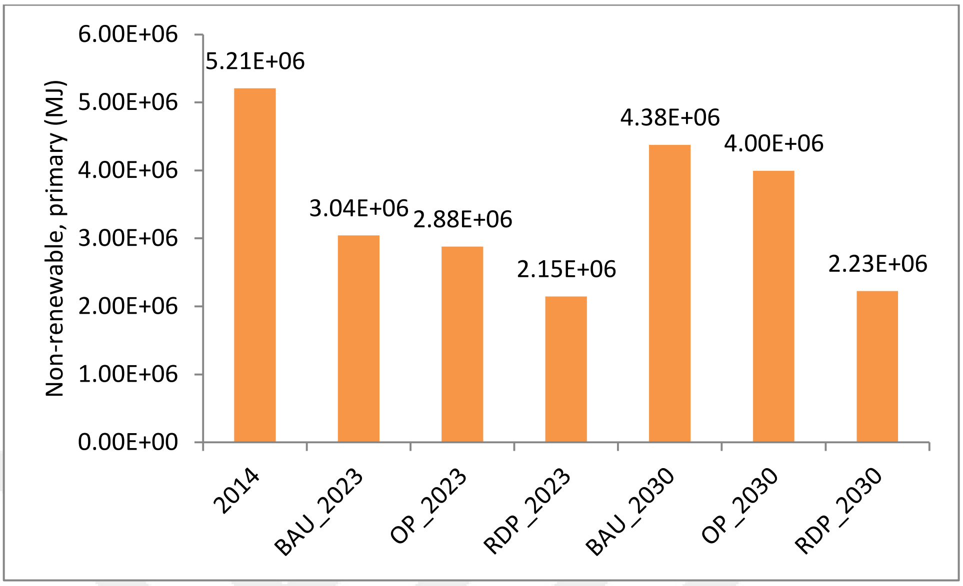


Figure 3.55 Comparison of non-renewable, primary CExD scores for future scenarios

Renewable, water CExD scores are mainly resulted from hydropower technologies. All of the scenarios propose that CExD scores almost remain the same for 2023 and 2030 projections in the scenario basis, yet they are higher than 2014 levels (**Figure 3.56**).

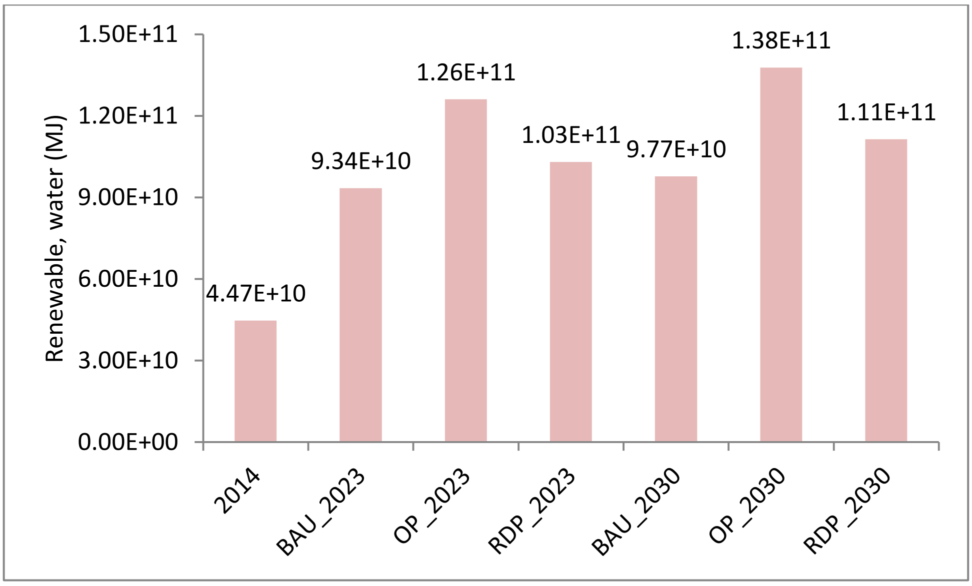


Figure 3.56 Comparison of renewable, water CExD scores for future scenarios

Non-renewable, metals CExD scores are lower for 2023 projections compared to 2014 levels for all scenarios. But 2030 scores are higher for BAU and OP scenarios while RDP score remains almost the same (**Figure 3.57**).

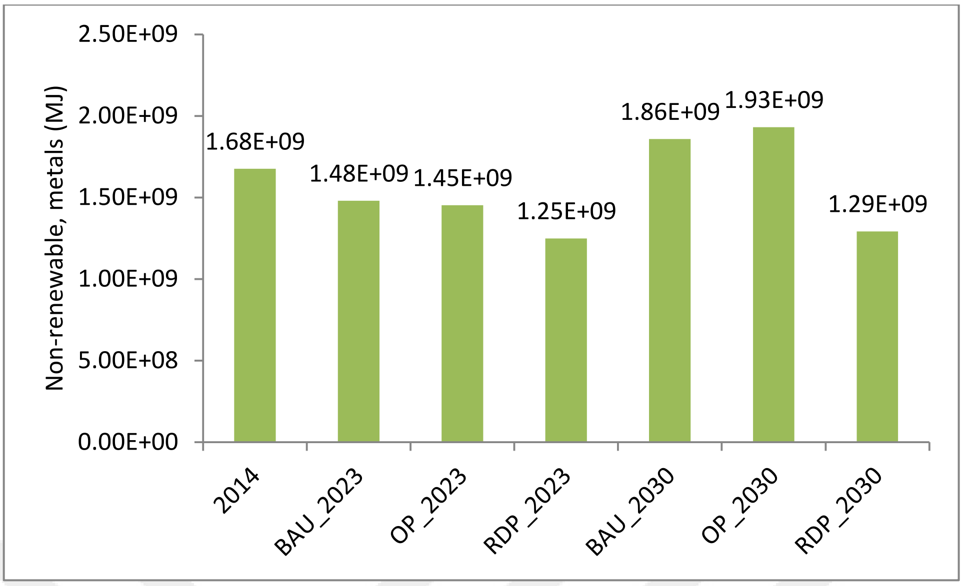


Figure 3.57 Comparison of non-renewable, metals CExD scores for future scenarios

Non-renewable, minerals score have an increasing trend for BAU scenario. OP and RDP scenarios propose lower demands for 2023 compared to 2014 levels. OP scores tend to increase in 2030 while RDP scores remain the same (**Figure 3.58**).

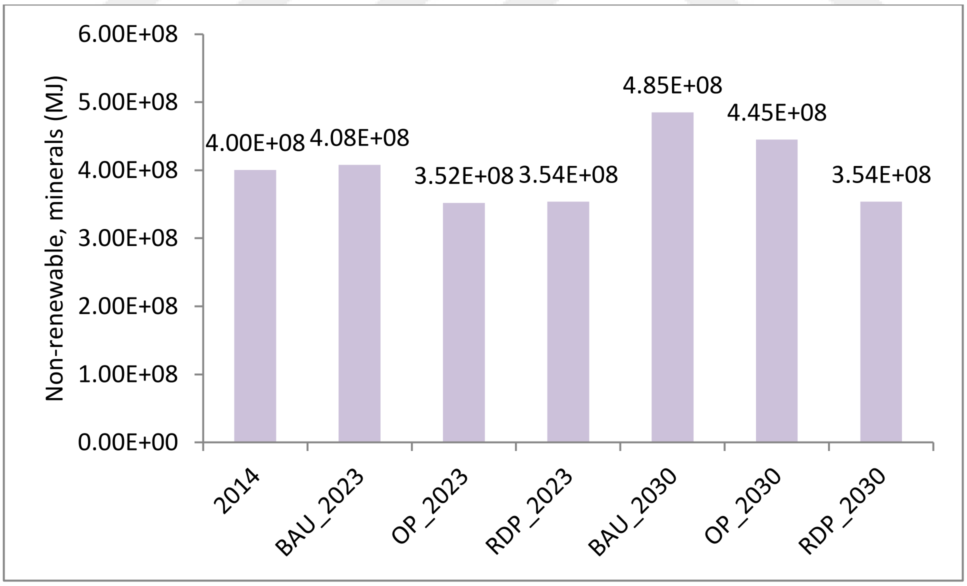


Figure 3.58 Comparison of non-renewable, minerals CExD scores for future scenarios

3.1.4.4 CML 2 baseline 2000

All of the ten categories have higher scores for the BAU and OP scenarios due to their high dependency of fossil fuel technologies. The reason of low scores for the RDP scenarios is because they depend on replacing fossil fuel technologies with renewable alternatives. A detailed analysis of each indicator is given below (See Appendix 11).

Abiotic depletion impact category scores result from extraction of minerals and fossil fuels. Since BAU scenario is highly dependent on fossil fuels, abiotic depletion scores are increasing in time compared with 2014 levels. OP scenario generation mix is dominated by fossil fuel and nuclear technologies, the resulting impacts tend to increase in time compared with 2014 levels. As the share of renewable technologies increases, the demand of fossil fuel extraction decreases. Abiotic depletion scores are kept 2014 levels and even below this level only if RDP scenario is applied (**Figure 3.59**).

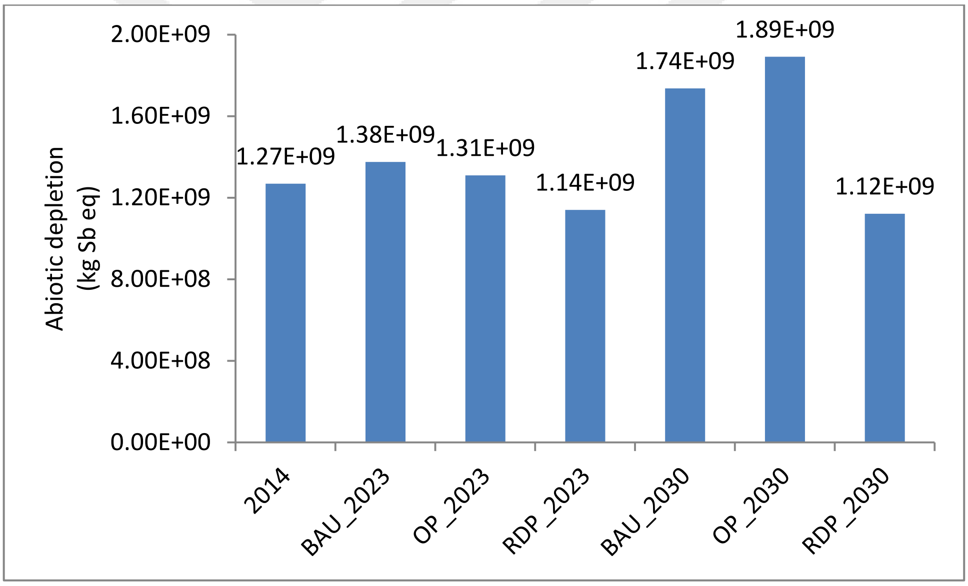


Figure 3.59 Comparison of abiotic depletion category scores via CML 2 Baseline 2000 method

Acidification describes the fate and deposition of acidifying substances. 2023 scores of all scenarios are higher than 2014 levels and 2030 scores indicate increasing trend in the impact. The impact category scores mainly resulted from the sulphur content of lignite and hard coal. Since OP scenario has higher share of lignite, the highest impact score belongs to this scenario followed by BAU. However, RDP scenario scores indicate that acidification scores can be retained in 2014 levels with the implementation of renewable technologies instead of fossil fuels (**Figure 3.60**).

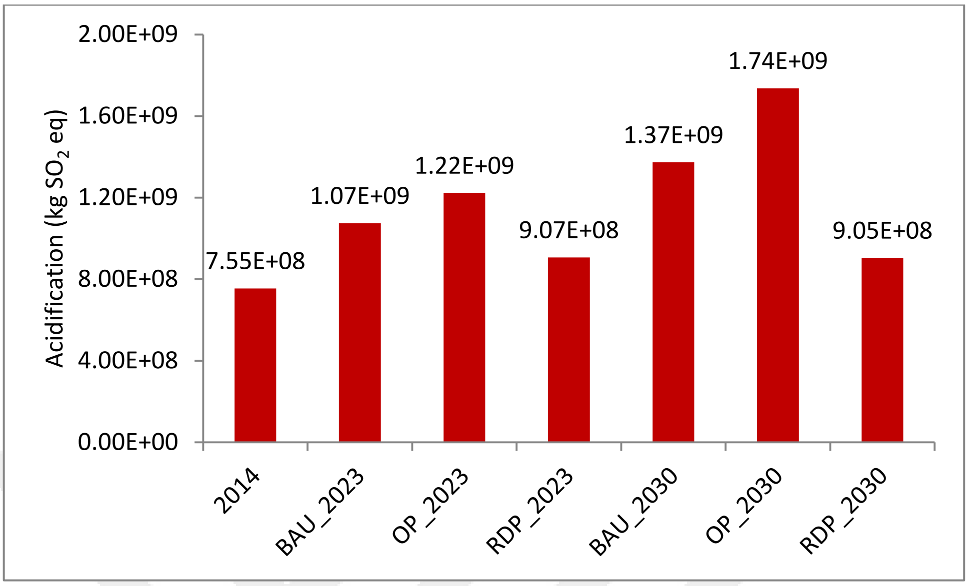


Figure 3.60 Comparison of acidification category scores via CML 2 Baseline 2000 method

Eutrophication includes all impacts due to excessive levels of macro-nutrients in the environment caused by emissions of nutrients to air, water and soil while operation of the power plant. BAU and OP scenario scores estimate a serious increase in the eutrophication levels compared to 2014. Yet, RDP scenario scores indicate the impact can remain almost the same if renewable shares increase (**Figure 3.61**).

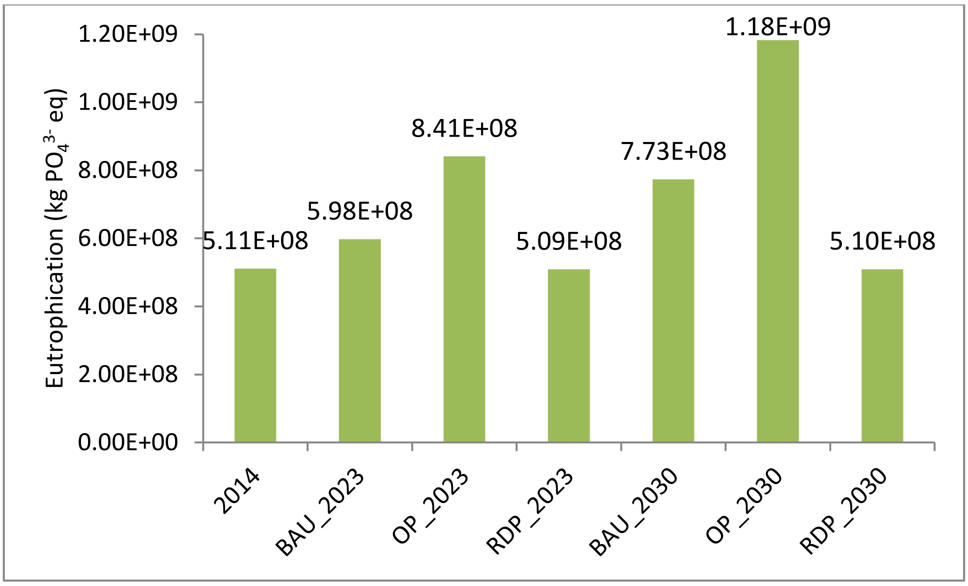


Figure 3.61 Comparison of eutrophication category scores via CML 2 Baseline 2000 method

Global warming (GWP100a) is related to emissions of greenhouse gases to air. The results are given for the time horizon of 100 years. Fossil fuel technologies are the main contributor to global warming potential due to their high carbon content. BAU and OP scenarios indicate increasing trends from 2014 to 2030. RDP scenario results show that the GWP scores can remain the same when renewable technologies implemented (**Figure 3.62**).

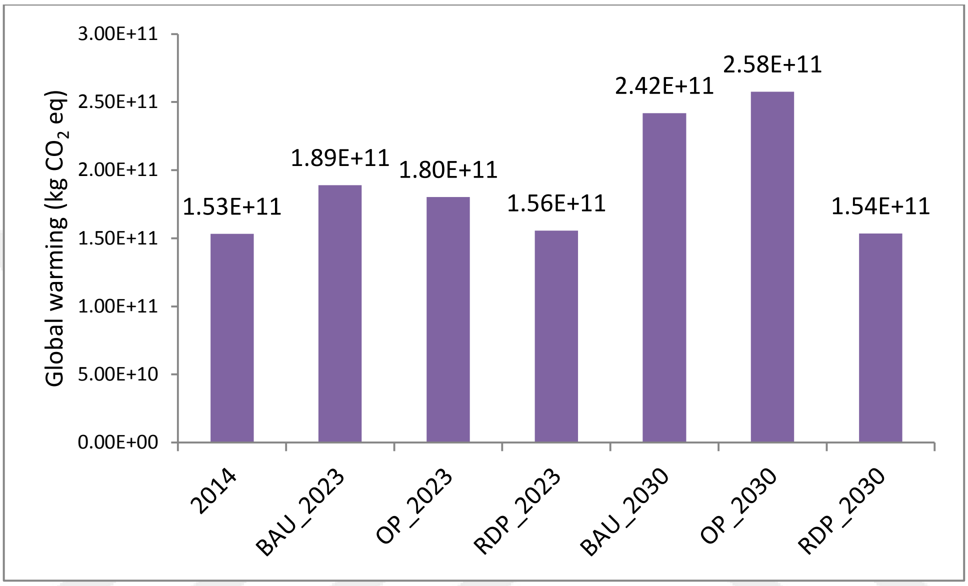


Figure 3.62 Comparison of global warming (GWP100a) category scores via CML 2 Baseline 2000 method

Ozone layer depletion scores are mainly caused by the extraction of gas and its long distance transport. BAU scenario is based on decreasing natural gas share in the generation mix, for this reason impact category scores tend to decrease for 2023. But as the total electricity generated increase in time, 2030 scores are greater than 2023 values. OP has the highest scores compared to other scenarios for each year. This may be due to the overestimated generation demand. RDP scenario has increasing scores for 2023 and 2030, yet the 2030 levels are still lower than 2014 values (**Figure 3.63**).

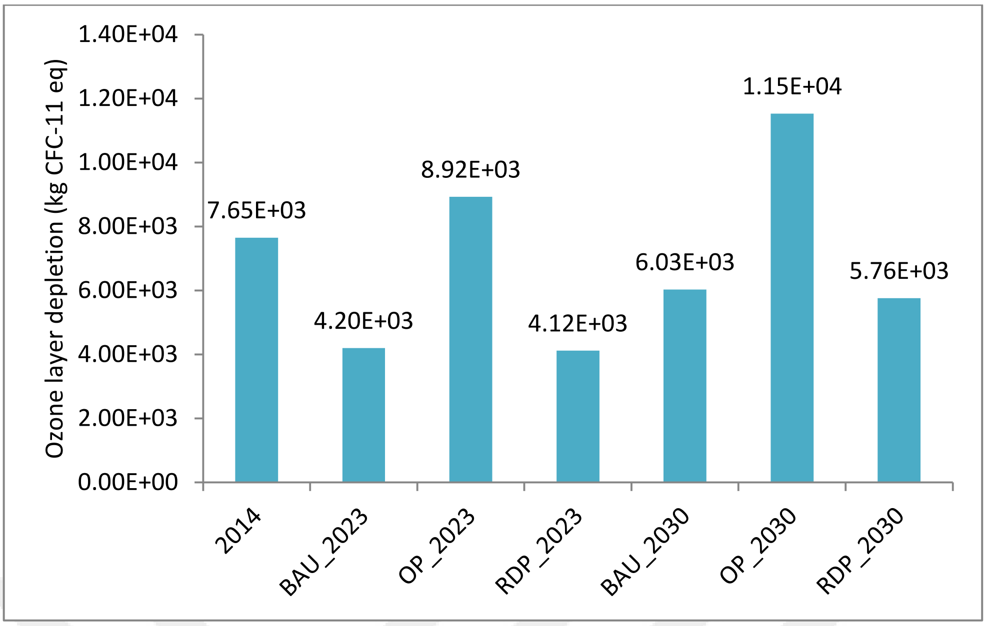


Figure 3.63 Comparison of ozone layer depletion category scores via CML 2 Baseline 2000 method

Human toxicity concerns the effects of toxic substances on the human environment especially from the heavy metal emissions during power plant operation. BAU and OP scenarios have increasing scores for future projections due to high fossil fuel share while RDP offers almost constant impacts throughout the years (**Figure 3.64**).

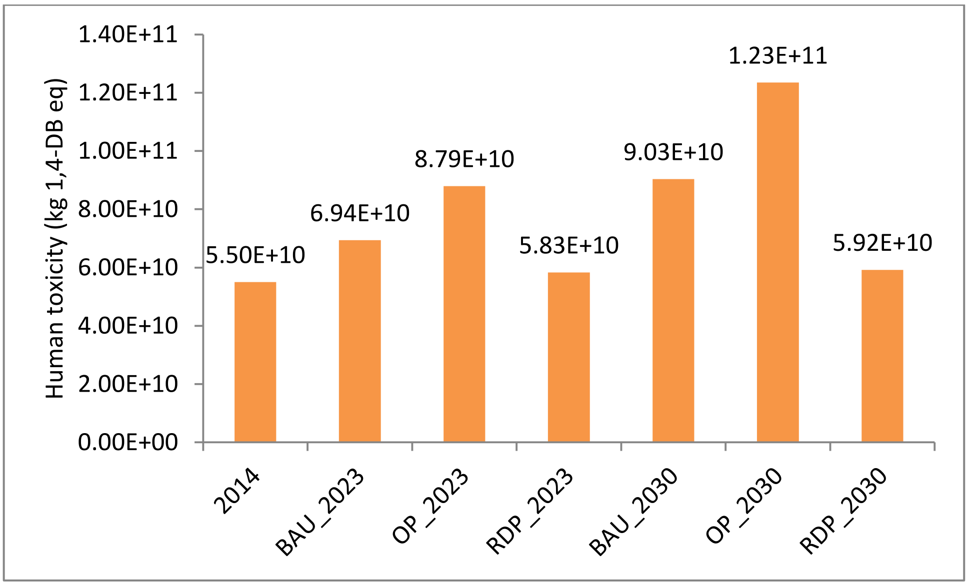


Figure 3.64 Comparison of human toxicity category scores via CML 2 Baseline 2000 method

Fresh water aquatic ecotoxicity refers to the impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water and soil. Similar to human toxicity scores, BAU and OP scenarios have increasing scores for future projections while RDP scores remain almost the same throughout the years (**Figure 3.65**).

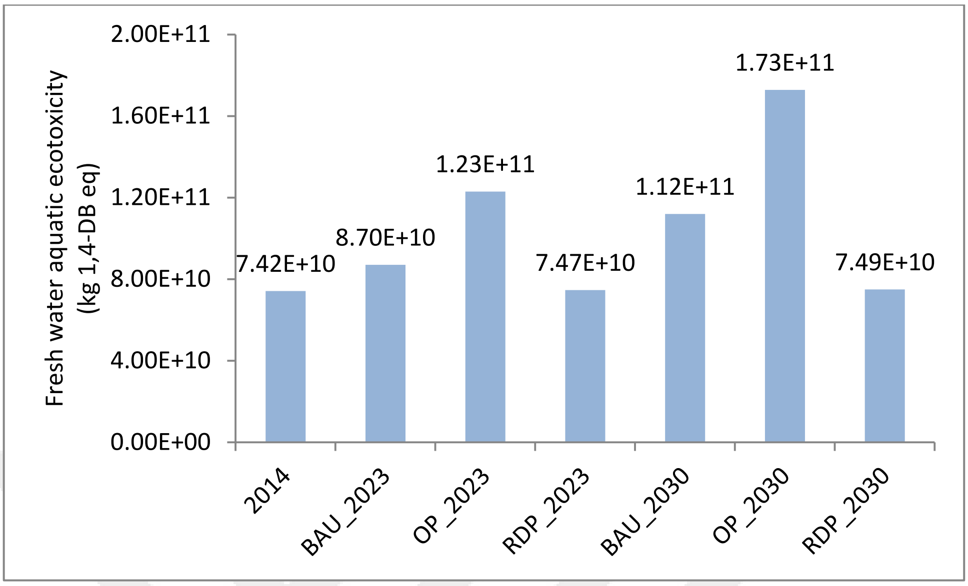


Figure 3.65 Comparison of fresh water aquatic ecotoxicity category scores via CML 2 Baseline 2000 method

Marine aquatic ecotoxicity refers to impacts of toxic substances on marine ecosystems, as a result of emissions of toxic substances to air, water and soil. High fossil fuel share results in higher scores for BAU and OP scenarios while RDP scenario offers almost constant impact scores for future projections (**Figure 3.66**).

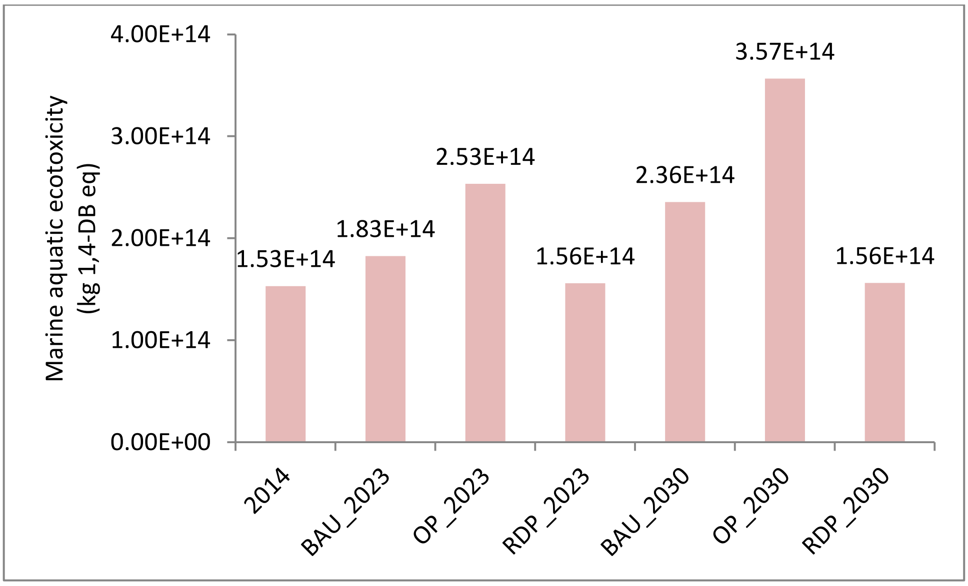


Figure 3.66 Comparison of marine aquatic ecotoxicity category scores via CML 2 Baseline 2000 method

Terrestrial ecotoxicity refers to impacts of toxic substances on terrestrial ecosystems, as a result of emissions of toxic substances to air, water and soil. Like the other toxicity scores, BAU and OP scores are higher compared to RDP scores (**Figure 3.67**).

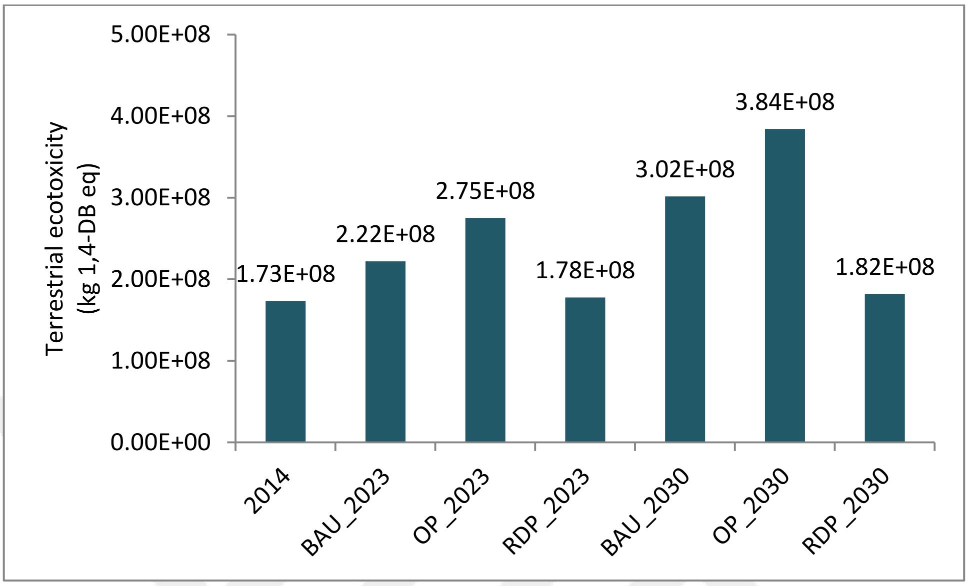


Figure 3.67 Comparison of terrestrial ecotoxicity category scores via CML 2 Baseline 2000 method

Photochemical oxidation impact is mainly caused from extraction and operation of fossil fuels. As a result, BAU and OP scenarios have higher scores than RDP scenario (**Figure 3.68**).

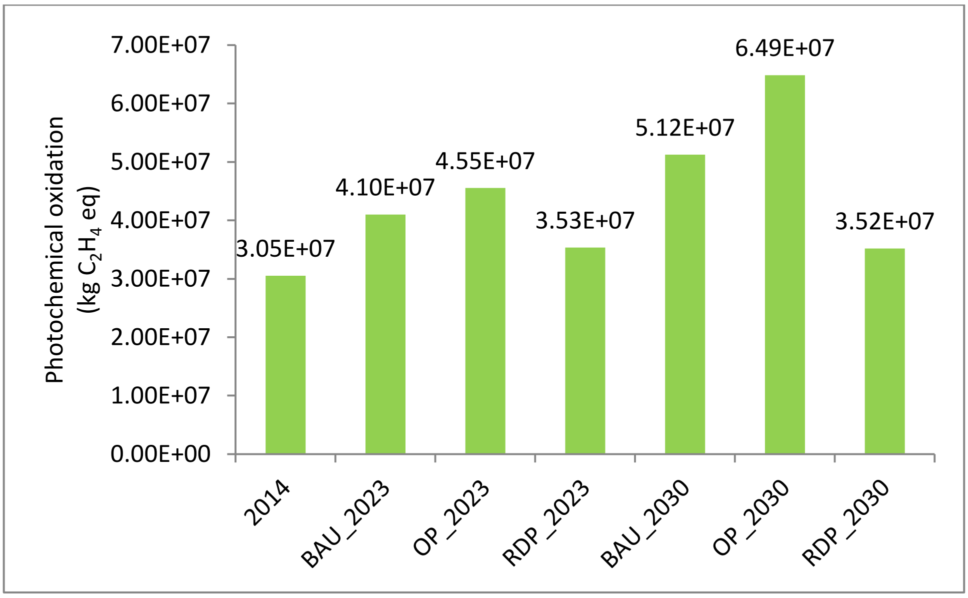


Figure 3.68 Comparison of photochemical oxidation category scores via CML 2 Baseline 2000 method

3.1.4.5 ReCiPe (H) midpoint

ReCiPe (H) midpoint method results are tabulated in Appendix A12. *Climate change* category scores mainly caused from greenhouse gas emissions due to high carbon content of fossil fuels. Therefore, scenarios with high fossil fuel technologies have higher scores for future projections as seen BAU and OP results. RDP scenario claims the same levels can be retained if renewable technologies are implemented (**Figure 3.69**).

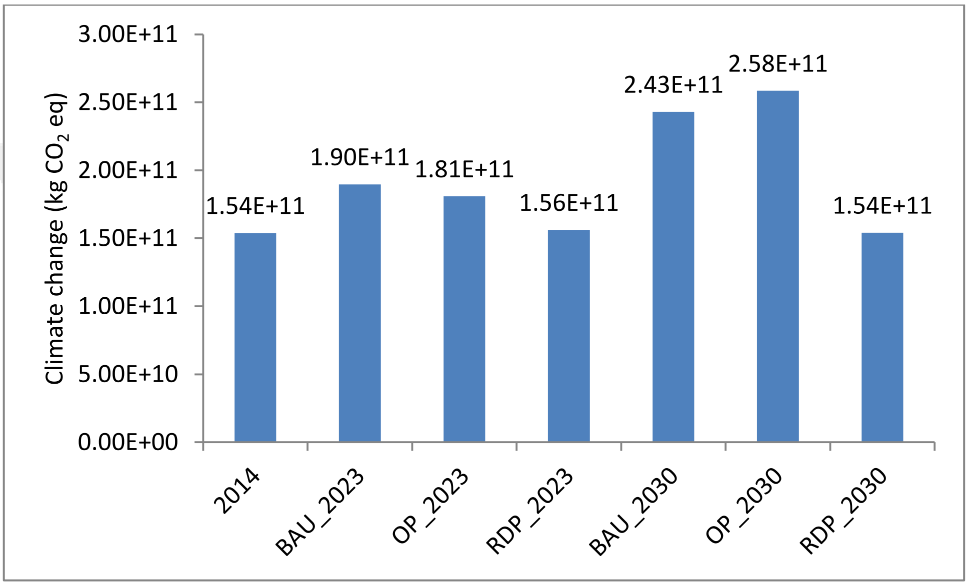


Figure 3.69 Comparison of climate change category scores via ReCiPe (H) midpoint method

Ozone depletion is mainly caused by the extraction of gas and its long distance transport. BAU scenario is based on decreasing natural gas share in the generation mix, for this reason impact category scores tend to decrease for 2023. But as the total electricity generated increase in time, 2030 scores are greater than 2023 values. OP has the highest scores compared to other scenarios for each year. This may be due to the overestimated generation demand. RDP score have an increasing trend for 2023 and 2030, yet the 2030 levels are exceedingly lower than 2014 values (**Figure 3.70**).

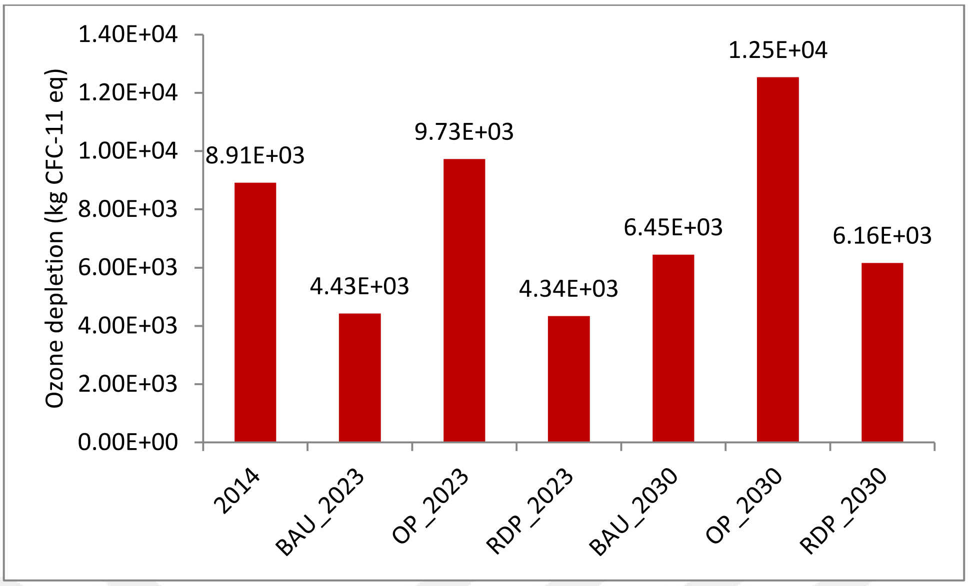


Figure 3.70 Comparison of ozone depletion category scores via ReCiPe (H) midpoint method

Terrestrial acidification scores are mainly resulted from the sulphur content of lignite and hard coal. Future scenarios with high fossil fuel shares have higher scores as a result. BAU and OP scenarios have increasing scores until 2030 while RDP scores increase slightly compared to them (**Figure 3.71**).

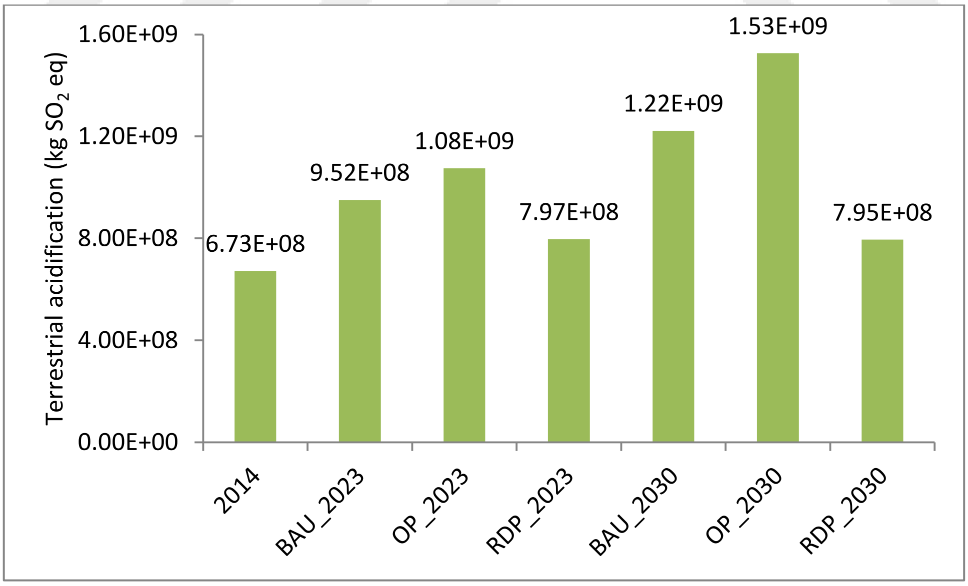


Figure 3.71 Comparison of terrestrial acidification category scores via ReCiPe (H) midpoint method

Freshwater eutrophication scores have the highest value for OP scenario due to its high total generation demand estimation. BAU scenario has moderately increasing scores while RDP scenario indicates the same levels for 2023 and 2030 (**Figure 3.72**).

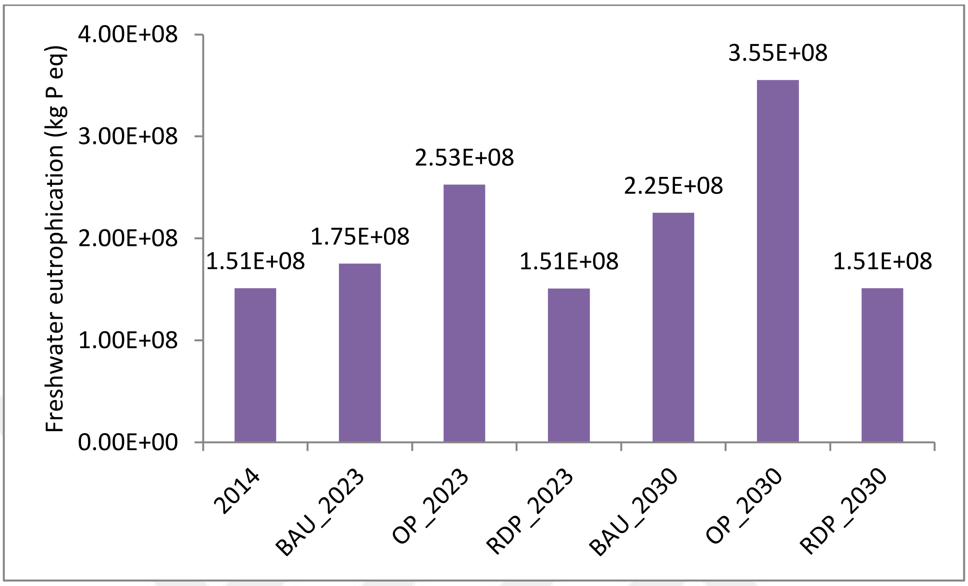


Figure 3.72 Comparison of freshwater eutrophication category scores via ReCiPe (H) midpoint method

Marine eutrophication scores show similar tendency to freshwater eutrophication results. BAU and OP scenarios have higher scores than RDP (**Figure 3.73**)

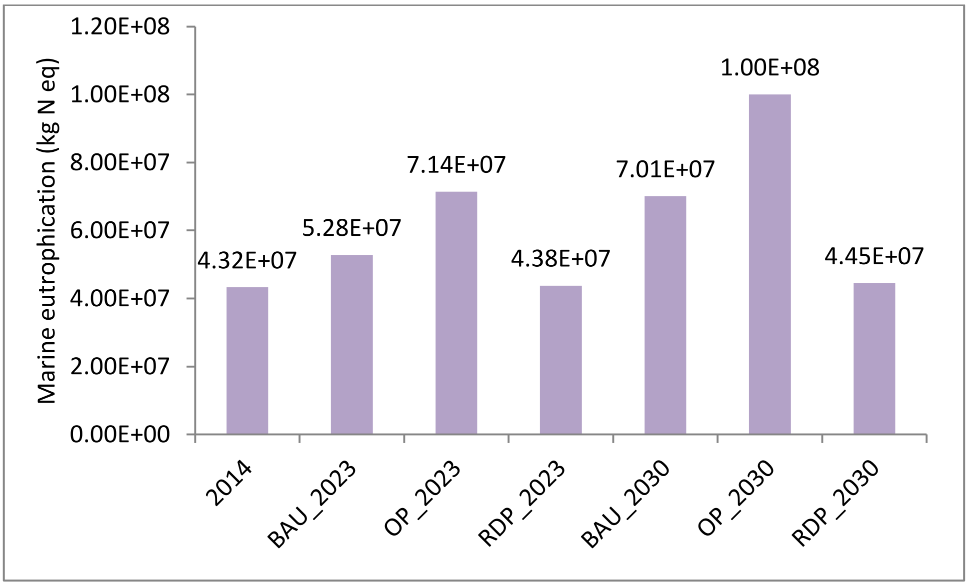


Figure 3.73 Comparison of marine eutrophication category scores via ReCiPe (H) midpoint method

Human toxicity scores are mainly caused by the emission of heavy metals during power plant operation. For 2023, BAU and RDP scenarios have similar scores with 2014 levels; but OP score is higher. BAU and OP scenario scores continue to increase until 2030 while RDP score retains the same level (**Figure 3.74**).

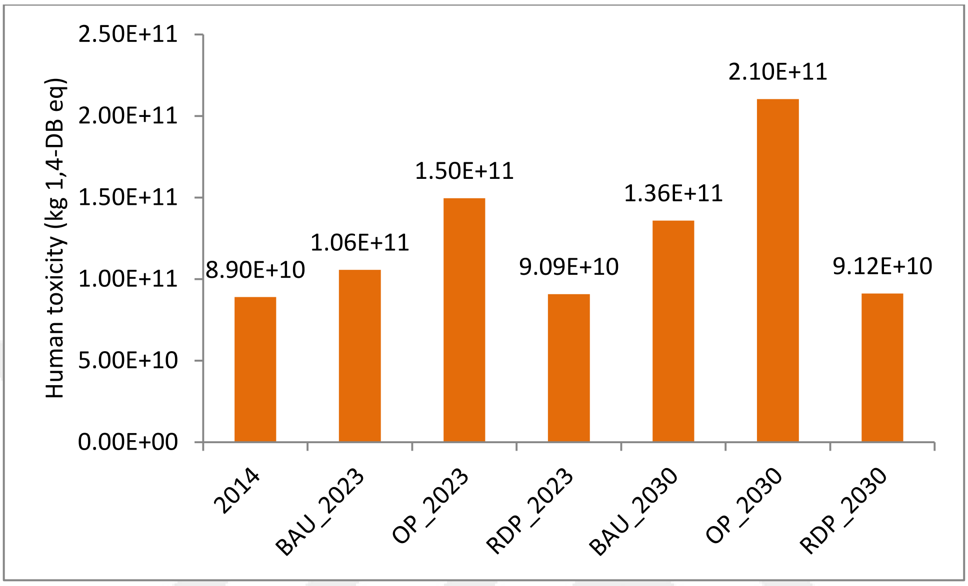


Figure 3.74 Comparison of human toxicity category scores via ReCiPe (H) midpoint method

Photochemical oxidant formation scores mainly resulted from power plant operation – especially as a result of the combustion process. BAU and OP have very close scores for 2023 and 2030 due to their coal shares. As their score increase until 2030, RDP sustains the same levels with 2014 via renewable technologies (**Figure 3.75**).

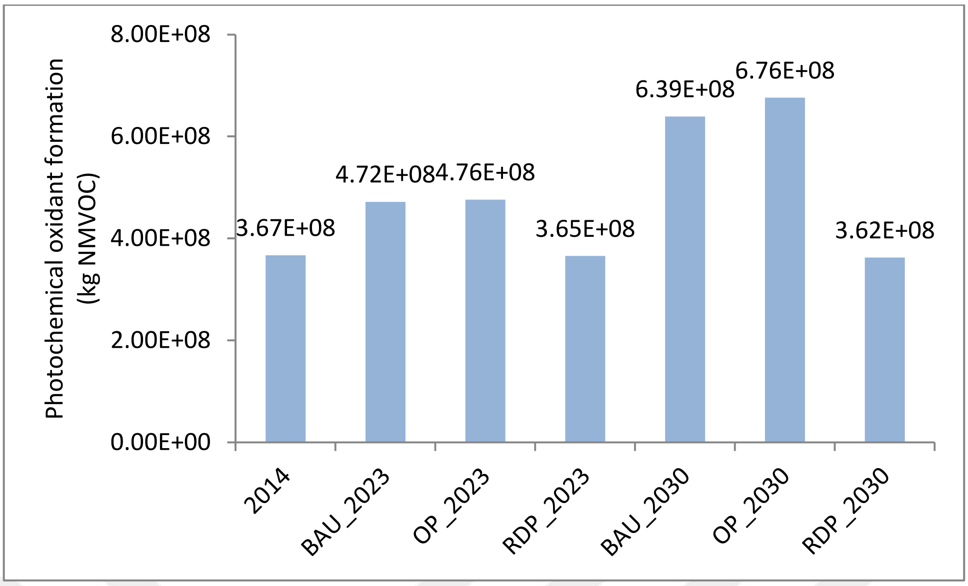


Figure 3.75 Comparison of photochemical oxidant formation category scores via ReCiPe (H) midpoint method

Particulate matter formation scores are mainly based on the amount of fine particulate matters with a diameter of less than 10 µm (PM10). The particulate matter formation scores have the highest value for scenarios with high lignite technology due to its high ash content. As a result of having a higher share, OP scenario has the highest scores. BAU scenario has moderately increasing scores while RDP scores remains at the same levels with 2014 impacts (**Figure 3.76**).

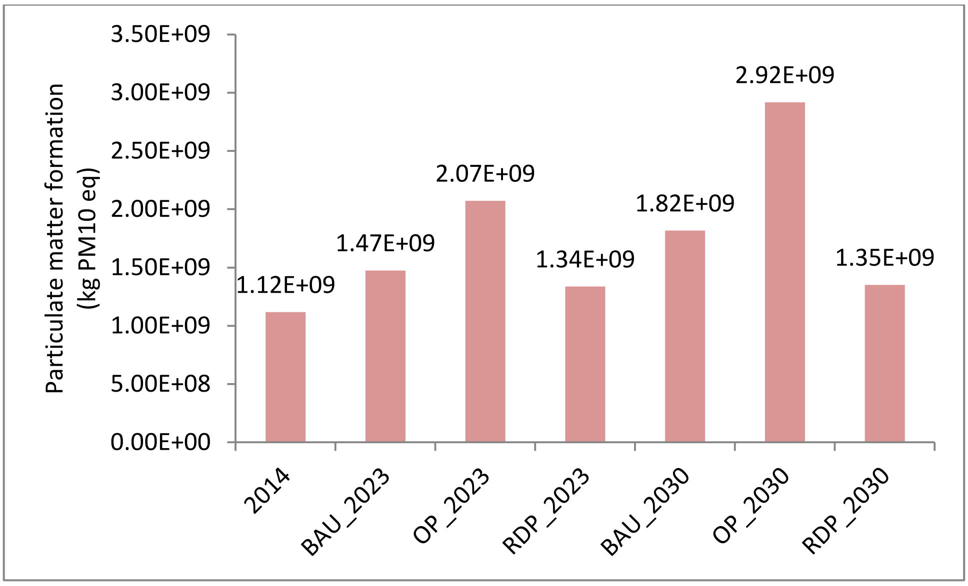


Figure 3.76 Comparison of particulate matter formation category scores via ReCiPe (H) midpoint method

Terrestrial ecotoxicity scores are mainly caused from the heavy metal emissions during power plant operation. Solar PV technology contributes to this category impacts along with fossil fuels. For this reason, RDP scenario results show similar impacts with other scenarios in 2023. However, for 2030, RDP impact remains the same as 2023 levels while BAU and OP scores are increasing (**Figure 3.77**).

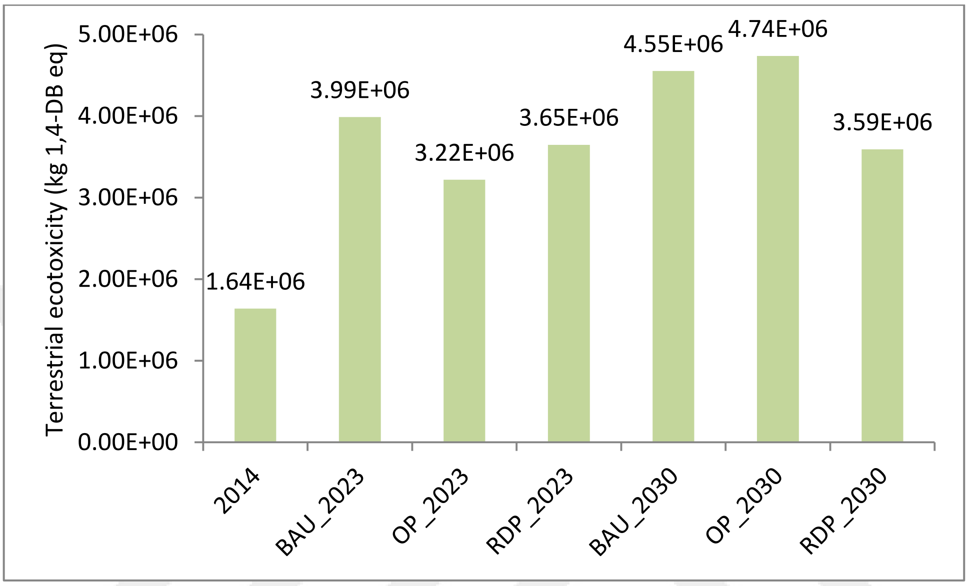


Figure 3.77 Comparison of terrestrial ecotoxicity category scores via ReCiPe (H) midpoint method

Freshwater ecotoxicity scores are also resulted from heavy metal emissions during power plant operation especially lignite and coal technologies. As OP scenario has the highest lignite share for future projections, freshwater ecotoxicity scores are quite higher than the other scenarios. BAU scenario has moderately high scores even they increase until 2030. RDP scenario results show that the impact level retains the same as 2014 in case of renewable technology implementation (**Figure 3.78**).

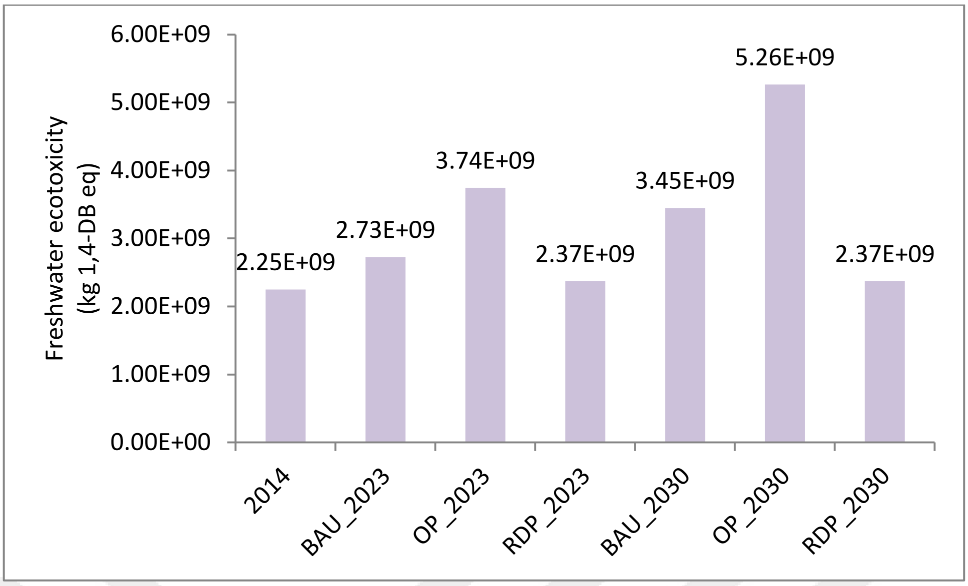


Figure 3.78 Comparison of freshwater ecotoxicity category scores via ReCiPe (H) midpoint method

Marine ecotoxicity category scores are similar to freshwater ecotoxicity and result from the heavy metal emissions during power plant operation. The scores are the highest for OP due to high lignite share. BAU scenario has moderate scores while RDP scores remain the same with 2014 levels (**Figure 3.79**).

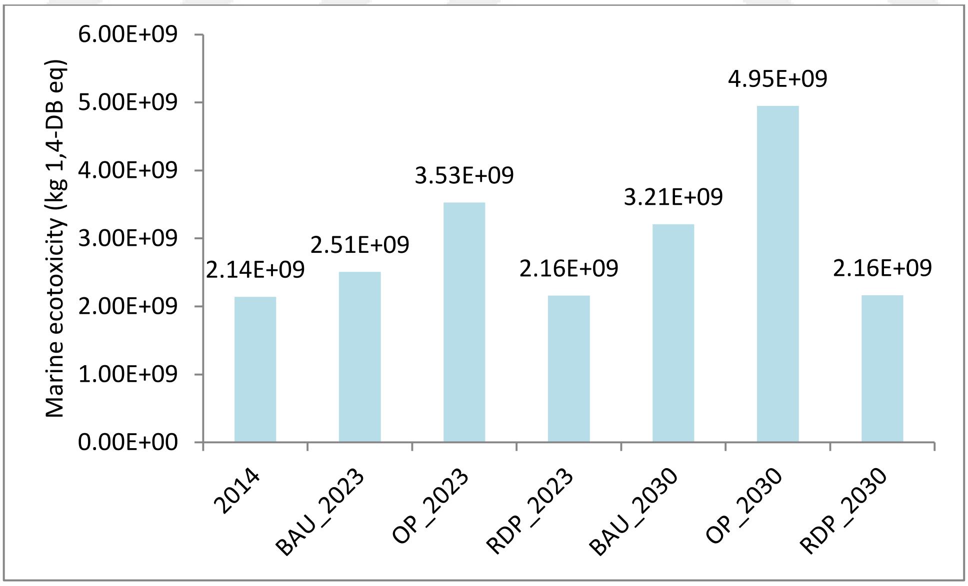


Figure 3.79 Comparison of marine ecotoxicity category scores via ReCiPe (H) midpoint method

Ionising radiation scores are largely caused by the release of radioactive material to the environment. Since there is no nuclear power plant in operation for 2014, all of the future projections have significantly higher scores for this impact category. OP has the highest scores for this impact category but, as mentioned before, OP scenario assumptions may overestimate the future projections. BAU and RDP are very close to each other since their projections are the same for generation from nuclear technologies (**Figure 3.80**).

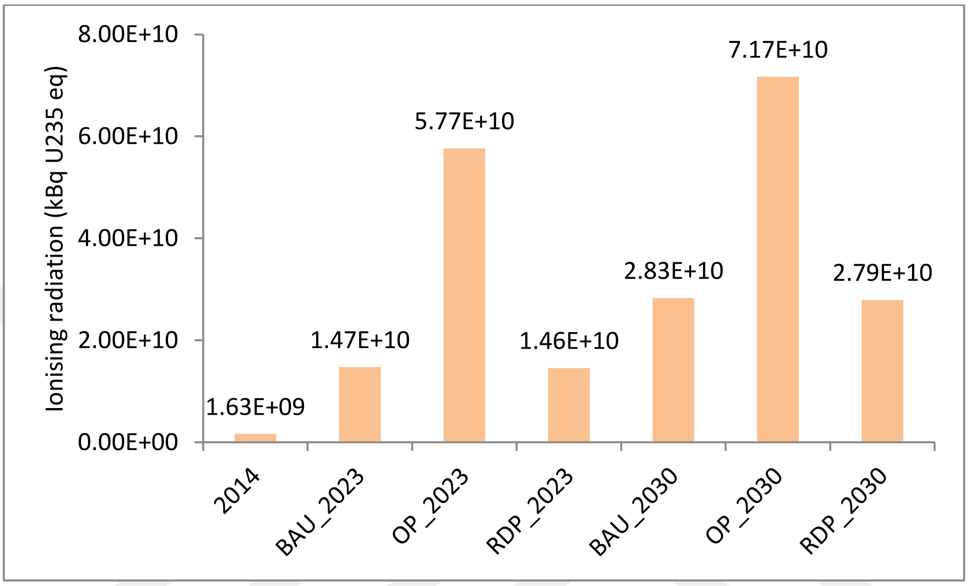


Figure 3.80 Comparison of ionising radiation category scores via ReCiPe (H) midpoint method

Agricultural land occupation scores are mainly resulted from the hard coal technology due to the mining and power plant construction activities. Since BAU scenario proposes higher share of coal, its score is the highest among future projections. OP has moderately increasing scores while RDP suggest a decreasing trend even lower 2014 levels *(***Figure 3.81***).*

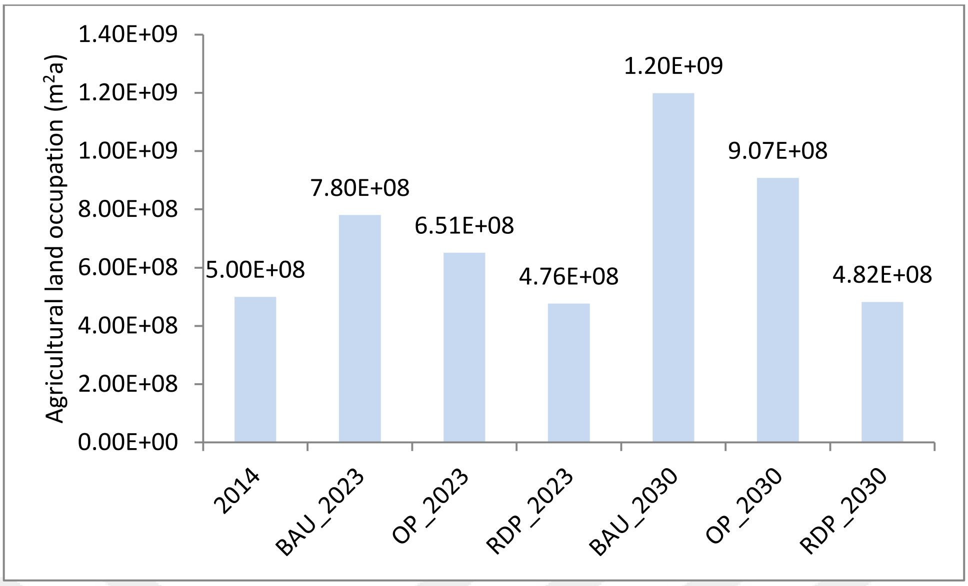


Figure 3.81 Comparison of agricultural land occupation category scores via ReCiPe (H) midpoint method

Urban land occupation scores have similar trend with agricultural land occupation scores. Similarly, BAU has the highest impact score while OP has moderately increasing scores. RDP scores are decreasing due to the lower share of hard coal technology than 2014 levels (**Figure 3.82**).

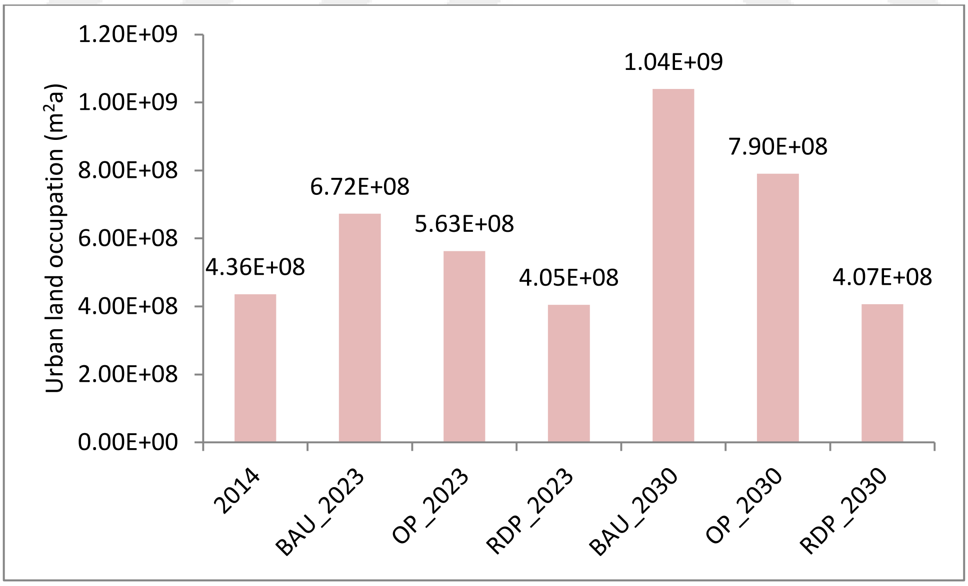


Figure 3.82 Comparison of urban land occupation category scores via ReCiPe (H) midpoint method

Natural land transformation scores are mainly resulted from conventional natural gas technology and hydropower with dam due to fuel extraction and power plant construction. Since natural gas technology share is substituted by hydropower technology in all future scenarios, impact scores are close to each other for all cases and also almost the same as 2014 levels (**Figure 3.83**).

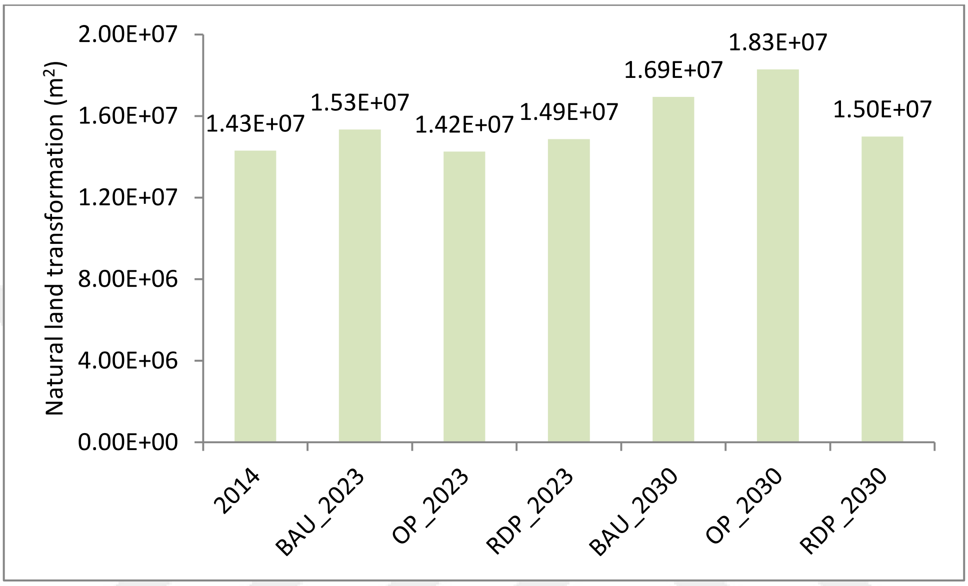


Figure 3.83 Comparison of natural land transformation category scores via ReCiPe (H) midpoint method

Water depletion scores are mainly resulted from hydropower with dam technologies. As the share of renewable technologies increase in all future scenarios, water depletion impact scores are exceedingly higher for all projections. OP scenario has the highest score while BAU and RDP scenarios show similar impact results (**Figure 3.84**).

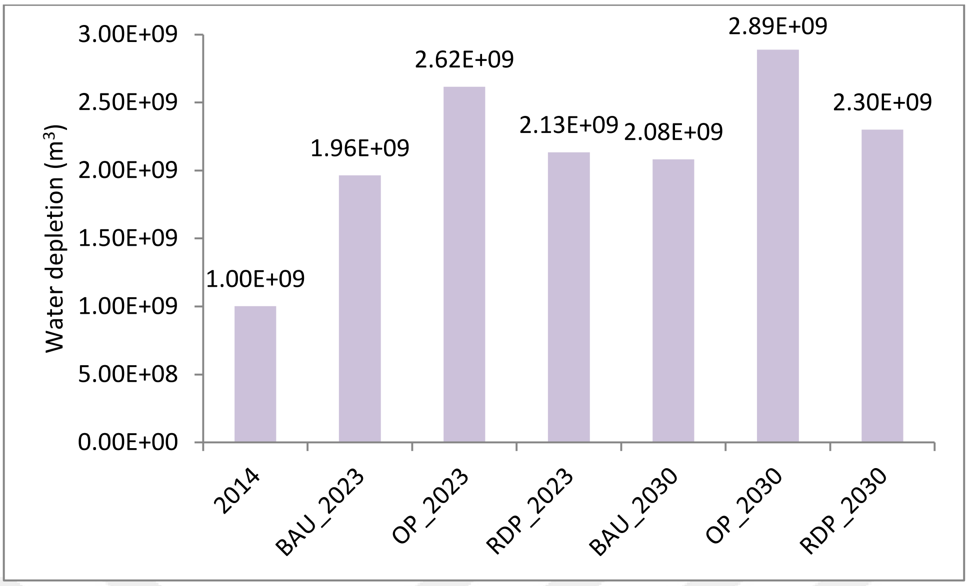


Figure 3.84 Comparison of water depletion category scores via ReCiPe (H) midpoint method

Metal depletion scores are mainly resulted from run-of-river hydropower and natural gas power plants. As the natural gas share is substituted by renewable technologies, RDP scenario scores are relatively lower than 2014 levels for future projections. BAU scenario proposes a lower level of natural gas in 2023 compared to 2014 and then the share increases for 2030. As a result, metal depletion scores decrease in 2023 but then increase until 2030. OP scenario has the highest scores due to its high electricity demand projection (**Figure 3.85**).

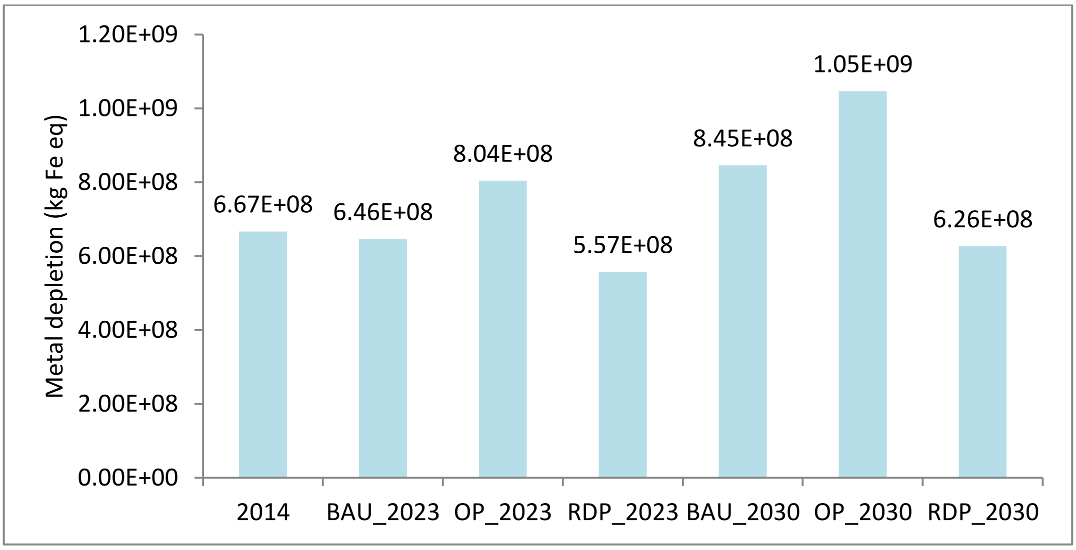


Figure 3.85 Comparison of metal depletion category scores via ReCiPe (H) midpoint method

Fossil depletion scores are expectedly high for scenarios with high fossil fuel share. Even the fossil fuel share decrease for BAU scenario, it has increasing scores until 2030. This is mainly due to the rising electricity generation demand in future projections. Because of the same reason, OP scenario scores show increasing trend even the share of fossil technologies remain almost the same. RDP scenario proposes a slight decline in the fossil depletion scores until 2030 due to the rising share of renewables (**Figure 3.86**).

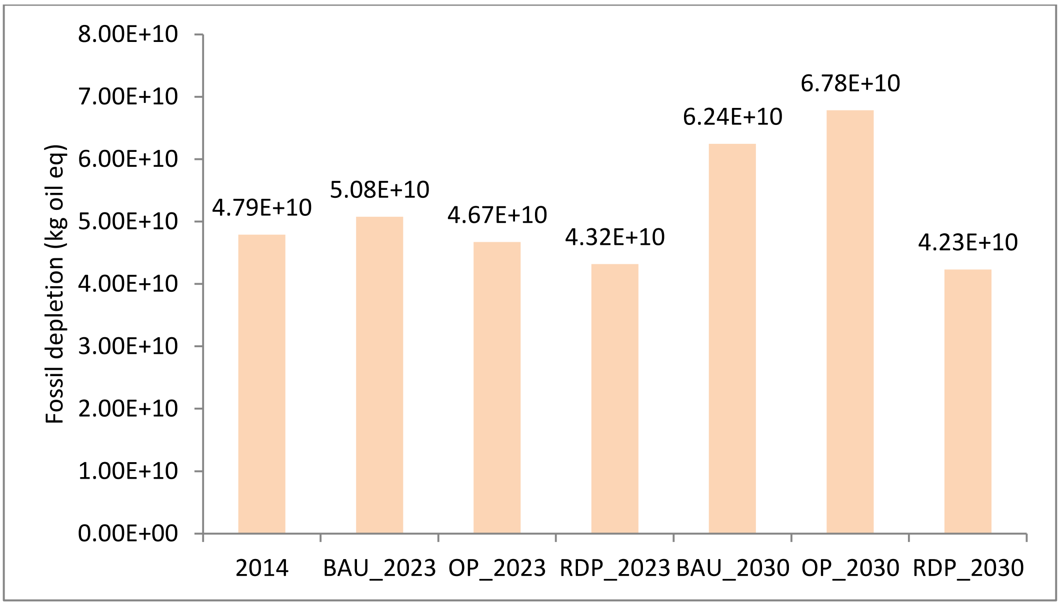


Figure 3.86 Comparison of fossil depletion category scores via ReCiPe (H) midpoint method

Even the same categories exist for CML 2 Baseline 2000 and ReCiPe (H) midpoint methodologies, some indicator scores do not overlap across these methods. For example, terrestrial ecotoxicity scores are different for CML 2 Baseline 2000 and ReCiPe (H) midpoint methodologies. This result is mainly due to the uncertainties about the assumptions of the method. CML 2 Baseline 2000 method considers a timeframe of infinity for the terrestrial ecotoxicity category while ReCiPe (H) midpoint category is based on a hundred years. As mentioned in the Section 2.1.3.2, three perspectives are considered for the ReCiPe method calculations; namely individual (I), and hierarchist (H), and egalitarian (E). According to the selected perspective, the differences in the assumptions result in varying scores of the indicators.

3.1.4.6 ReCiPe (H) endpoint

In order to obtain a representative single score from the numerous midpoint categories, ReCiPe (H) endpoint method is employed. From the midpoint category scores three endpoint categories are calculated, then these three category scores are aggregated into a single score (See Appendix A13).

Human health damage category scores for BAU and OP scenarios are significantly higher than the 2014 levels for 2023 and tend to increase until 2030. However, RDP scores remain almost the same for future projections. *Ecosystems* damage category scores almost the same as 2014 levels for 2023. BAU and OP scenarios have increasing scores while RDP proposes almost the same levels until 2030. Similar to ecosystems category results, *resource surplus costs* scores nearly the same as 2014 levels for 2023 (**Figure 3.87**).

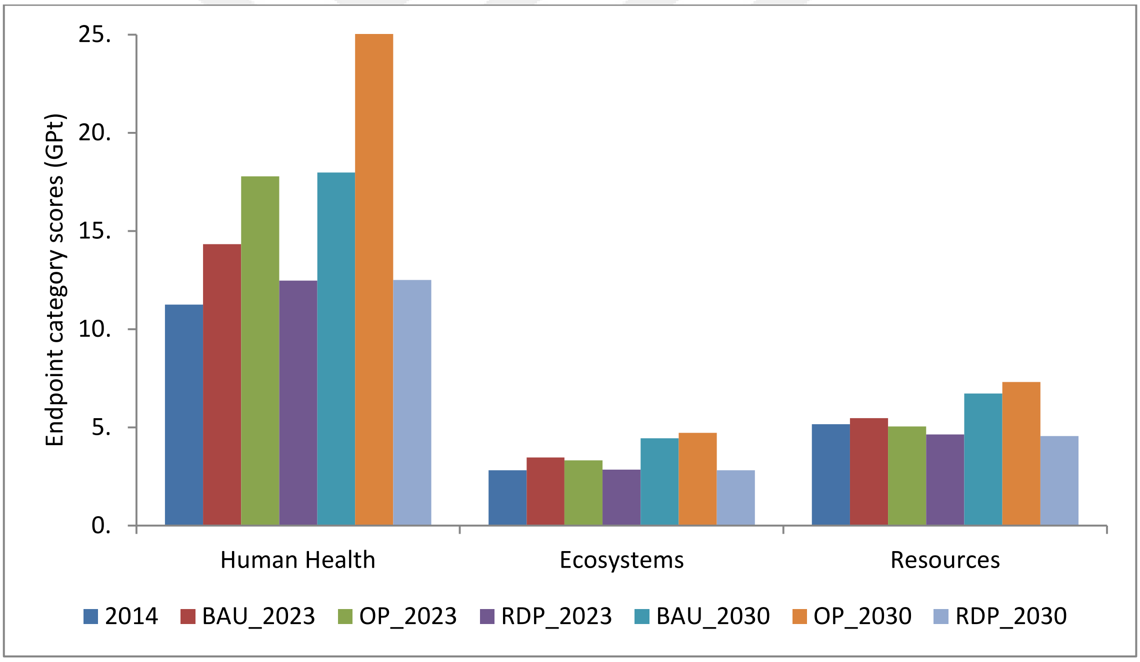


Figure 3.87 Damage category scores for future scenarios via ReCiPe (H) endpoint method

Single score results indicate that OP and BAU scenarios have increasing damage potential for future projections. 2014 levels can only be sustained if RDP scenario is put into practice (**Figure 3.88**).

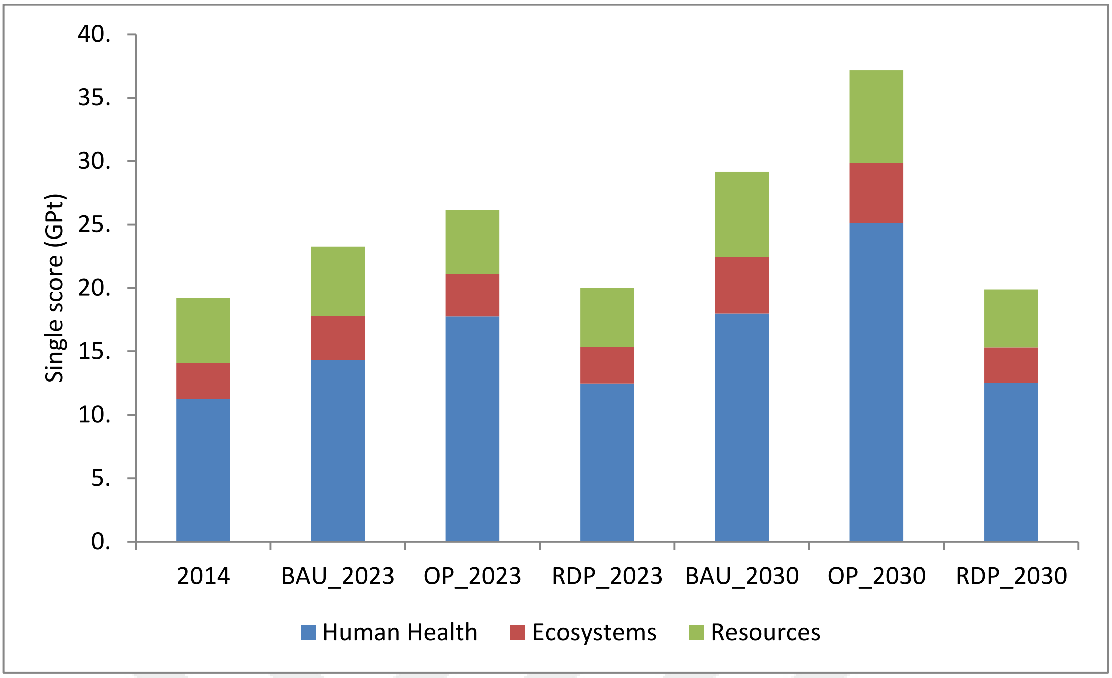


Figure 3.88 Single scores for future scenarios via ReCiPe (H) endpoint method

3.1.5 Comparison of the LCA results with literature

In order to check the consistency of LCA results, first, GWP (100a) is selected as the base category for the comparison of different methodologies considering the year 2014. GWP (100a) is selected because it is the common indicator for IPCC 2013, CML 2 Baseline 2000, and ReCiPe (H) midpoint methods. The results show that 2014 GWP (100a) scores are 1.56E+11, 1.53E+11, and 1.54E+11 kg CO_2-eq for IPCC 2013, CML 2 Baseline 2000, and ReCiPe (H) midpoint methods, respectively. The scores are significantly close to each other, indicating that the methods are consistent.

In addition, previously published papers in the literature are investigated for comparison, too. Yet, there are only two LCA studies for Turkey with a scope of cradle to grave but for the years 2010 and 2012 (Atılgan and Azapagic, 2016, Günkaya et al., 2016). These studies examine the electricity generation technologies with two different versions of CML methodology; CML 2001 and CML-IA (v.3.00). Apart from the abiotic depletion category, all indicators can be compared to the results of this study. The comparison shows that the computation results of this study are consistent with the previously published scores.

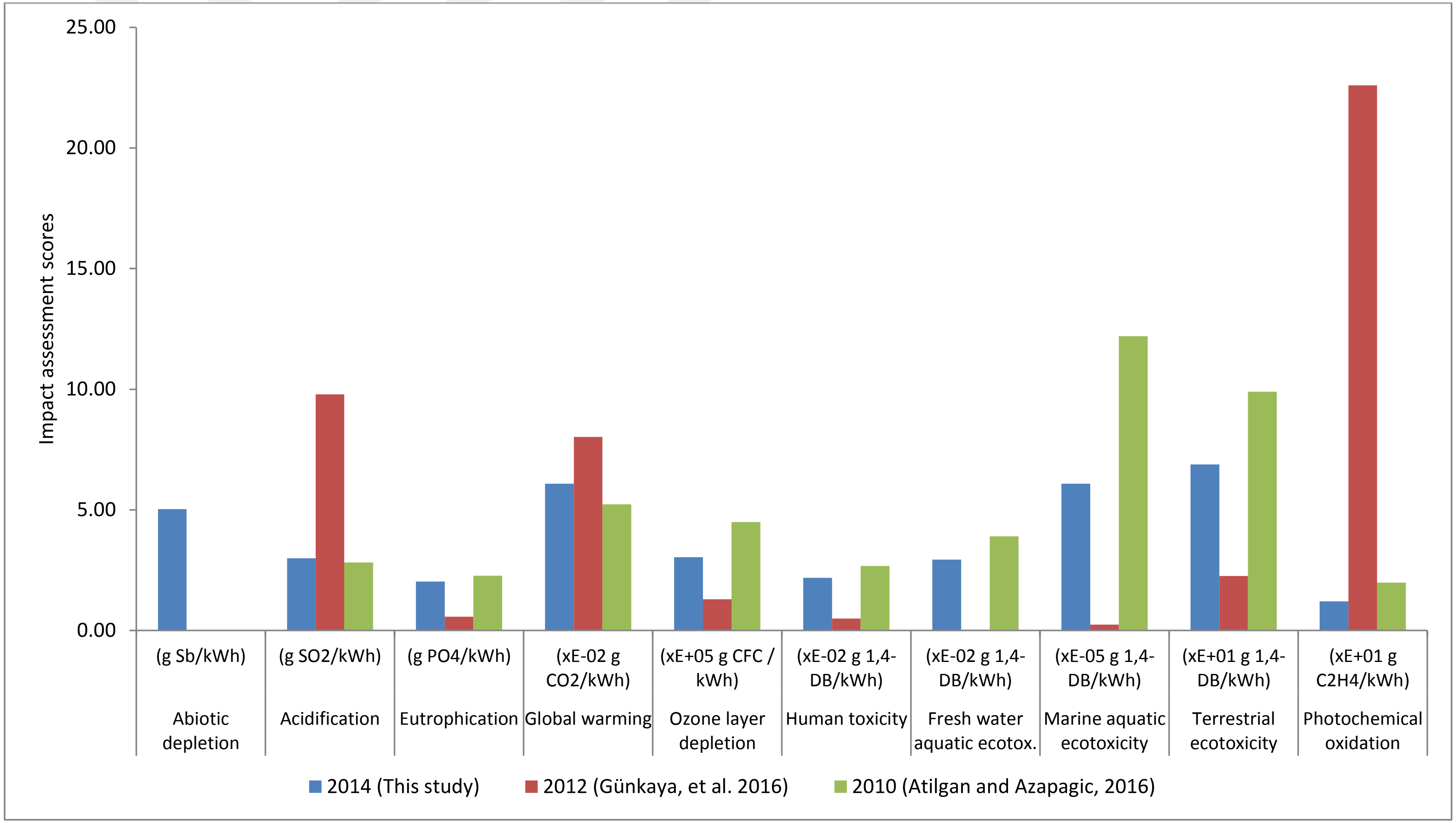


Figure 3.89 Comparison of LCA scores with literature

3.2 Multi Criteria Decision Analysis (MCDA)

As mentioned before, MCDA methodology is applied for further investigation of the electricity generation technologies available in 2014 in Turkey from different perspectives also known as sensitivity cases.

3.2.1 Evaluation of the sustainability indicators

Sustainability indicators are evaluated with country-specific data from official reports, statistics, papers and online databases when reliable data is accessible. But for some cases, it is not possible to gather Turkey specific indicator values since the lack of data published in the literature. Then, European countries, OECD countries or World average values have to be used. In an effort to minimize the uncertainties caused by the different data sources, the value of an indicator is based on the same reference study in order to sustain the consistency of the data in the indicator basis. Detailed explanations of evaluation of indicators are given below.

3.2.1.1 Levelized cost of electricity (LCOE)

Levelized cost of electricity (LCOE) is used as the sole economic indicator since it is complex enough to consider capital expenditure, operational expenditure, and fuel cost as well as electrical efficiency and total electricity produced. Up to our knowledge, a full analysis of levelized cost of electricity generation technologies has not been published for Turkey, yet. IEA report indicates country specific LCOE for hydropower with dam and onshore wind technologies (IEA, 2015). For these two technologies, LCOE data is used for 7% discount rate. 7% discount rate is considered as the average data given in the IEA report. Also the rate is compared with the interest rate of Turkish banks for foreign investors in Euro basis which is calculated very close to 7%. Turkey specific LCOE for coal is stated in the study conducted by Bloomberg New Energy Finance (BNEF) (WWF, 2014). The report says LCOE differs between 80–105 USD/MWh. An average of 92.5 USD/MWh is used as a reference point. LCOE for natural gas and run-of-river hydropower plant is also reported for Turkey with 10% discount rate (Atilgan and Azapagic, 2016). In order to construct a constant basis, LCOE values are evaluated with respect to 7% discount rate and the values are calculated as 65 and 156 USD/MWh for run-of-river and natural gas, respectively. Turkey specific LCOE data for solar PV technology has not published in the literature yet, so European average data is used for calculations (WWF, 2014). WWF report gives a range of 140 – 180 USD/MWh for solar PV technologies; an average of 160 USD/MWh is selected (**Table 3.1**).

Table 3.1 Evaluation of the levelized cost of electricity (LCOE) scores

Technology	LCOE , USD/MWh	Normalized
Coal	93	0.6
Natural gas	156	0.0
Solar PV	160	0.0
Hydro (dam)	41	1.0
Hydro (run-of-river)	65	0.8
Wind (onshore)	73	0.7

3.2.1.2 Efficiency

The first technical indicator is efficiency. Efficiency scores of fossil fuel technologies are gathered from studies conducted for Turkey (Atilgan and Azapagic, 2015, Gunkaya et al., 2016). Efficiency rates of 38 and 52% are taken for coal and natural gas technologies, respectively. A standard PV module efficiency of 16% is considered for solar PV technology (IRENA, 2017). Hydropower efficiencies for dam and run-of-river plants are assumed to be 78 and 82%, respectively (Gunkaya et al., 2016). An average efficiency of 35% is used for onshore wind plants (Stein, 2013) (**Table 3.2**).

Table 3.2 Evaluation of the efficiency scores

Technology	Efficiency, %	Normalized
Coal	38	0.3
Natural gas	52	0.5
Solar PV	16	0.0
Hydro (dam)	78	0.9
Hydro (run-of-river)	82	1.0
Wind (onshore)	35	0.3

3.2.1.3 Flexibility

The second technical indicator is flexibility defined as the ability to respond to varying demand. This indicator has a qualitative manner and can be evaluated in three options: “yes, fast” (response generated immediately), “yes, slow” (response can be generated but requires some time to reactivate the system), and “no” (unable to generate energy on demand) (Maxim, 2014). Natural gas power plants are able to meet the emergency demands of the power supply system in a very short time. As a result, their flexibility is quite high. As well as natural gas power plants, hydropower plants with dam are capable of compensating sudden fluctuations in power demand. Similarly, their flexibility is as high as natural gas. Coal power plants operate continuously during the working period; but their start-up process requires some time for responding the urgent demand. For this reason, their flexibility score is not as high as natural gas or hydropower. Renewable technologies like wind, solar PV, and run-of-river cannot reply an emergency demand due to their intermittent nature. Their flexibility score is quite lower than the other technologies, even they are considered as inflexible. The benefit attribution of this indicator is positive; the higher the flexibility, the better is the score. For this reason, flexible technologies which are capable of responding urgent demand have the highest score, 1; while inflexible technologies have a score of zero (**Table 3.3**).

Table 3.3 Evaluation of the flexibility scores

Technology	Flexibility	Normalized
Coal	yes, slow	0.5
Natural gas	yes, rapid	1.0
Solar PV	no	0.0
Hydro (dam)	yes, rapid	1.0
Hydro (run-of-river)	no	0.0
Wind (onshore)	no	0.0

3.2.1.4 Electricity mix share

The third technical indicator is the contribution of each technology to the annual electricity production. Since 2014 is selected as the baseline year for the calculations, the electricity generation mix shares belonging this year are introduced to the calculations (TETC, 2014) (**Table 3.4**).

Table 3.4 Evaluation of the electricity mix share scores

Technology	Electricity mix share, %	Normalized
Coal	30.2	0.6
Natural gas	47.9	1.0
Solar PV	0.0	0.0
Hydro (dam)	11.3	0.2
Hydro (run-of-river)	4.8	0.1
Wind (onshore)	3.4	0.1

3.2.1.5 Capacity factor

The last technical indicator is the capacity factor which represents the ratio of the generated electricity, for the time considered to the energy that could have been generated at continuous full power operation. Capacity factors for fossil fuel technologies are assumed 85% since they operate in base load (IEA, 2015). Capacity factors for renewable energy technologies are largely site-specific, so Turkey-based factors are taken into consideration for these technologies (IEA, 2015, TENVA, 2017). The capacity factors are 54, 38, and 18% for hydropower both dam and run-of-river, wind, and solar PV, respectively (**Table 3.5**).

Table 3.5 Evaluation of the capacity factor scores

Technology	Capacity factor, %	Normalized
Coal	0.85	1.0
Natural gas	0.85	1.0
Solar PV	0.18	0.0
Hydro (dam)	0.54	0.5
Hydro (run-of-river)	0.54	0.5
Wind (onshore)	0.38	0.3

3.2.1.6 Climate change

The first environmental indicator is the climate change impact of the selected electricity generation technologies. The calculations are based on the life cycle assessment approach with ReCiPe midpoint (H) impact assessment method (See Section 3.1.4.5). Climate change impact results are expressed in g CO_2-equivalents per kWh electricity generated. Fossil fuel technologies have dramatically higher scores compared to renewable technologies (**Table 3.6**).

Table 3.6 Evaluation of the climate change scores

Technology	Climate change, g CO_2-eq/kWh	Normalized
Coal	1192	0.0
Natural gas	482	0.6
Solar PV	3.55	1.0
Hydro (dam)	50.38	1.0
Hydro (run-of-river)	11.27	1.0
Wind (onshore)	0.09	1.0

3.2.1.7 Ozone depletion

The second environmental indicator is the ozone depletion resulting from the anthropogenic emissions of ozone depleting substances while power generation. The calculations are based on the life cycle assessment approach with ReCiPe midpoint (H) impact assessment method (See Section 3.1.4.5). Ozone depletion impact results are expressed in g CFC 11-equivalents per GWh electricity generated. Similar to climate change results, fossil technologies have higher scores than renewable technologies (**Table 3.7***)*.

Table 3.7 Evaluation of the ozone depletion scores

Technology	Ozone depletion, g CFC 11-eq/GWh	Normalized
Coal	4.24	0.9
Natural gas	67.70	0.0
Solar PV	0.70	1.0
Hydro (dam)	0.47	1.0
Hydro (run-of-river)	0.86	1.0
Wind (onshore)	0.03	1.0

3.2.1.8 Natural land transformation

The last environmental indicator is defined as the amount of natural land transformed and occupied for a certain time. The calculations are based on the LCA approach with ReCiPe midpoint (H) impact assessment method (See Section 3.1.4.5). Natural land transformation results are expressed in m^2 per GWh for each technology employed. Natural gas and hydropower with dam technologies require the highest natural land transformation followed by coal. However, in general, renewable technologies like solar PV and wind require less natural land than the others (**Table 3.8**).

Table 3.8 Evaluation of the natural land transformation scores

Technology	Natural land transformation, m^2/MWh	Normalized
Coal	36.3	0.6
Natural gas	70.26	0.2
Solar PV	0.51	1.0
Hydro (dam)	92.33	0.0
Hydro (run-of-river)	1.17	1.0
Wind (onshore)	0.06	1.0

3.2.1.9 Job creation

The first socio-economic indicator is the job creation expressed in “job-years” (a full time employee hired over 12 months) per unit of electricity produced. Job creation indicator scores cannot be gathered from Turkey-specific statistics and subsequently the scores are based on the previously published study (Wei et al., 2010) where a comprehensive literature survey is carried out and hydropower job creation score is gathered from elsewhere (Maxim, 2014). As mentioned in the International Labour Office (ILO) report, employment requirements associated with generation technologies vary in a very broad range when different studies investigated. But, generally, renewable energy sources create more jobs per GWh than non-renewable energy sources (ILO, 2018). The lowest job creation scores belong to fossil fuel technologies coal and natural gas while the highest score belongs to solar PV technology. The scores follow the main characteristics mentioned in the report (**Table 3.9**).

Table 3.9 Evaluation of the job creation scores

Technology	Job creation, job-yrs./GWh	Normalized
Coal	0.11	0.0
Natural gas	0.11	0.0
Solar PV	0.87	1.0
Hydro (dam)	0.55	0.6
Hydro (run-of-river)	0.27	0.2
Wind (onshore)	0.17	0.1

3.2.1.10 Social acceptability

The second socio-economic indicator is social acceptability. This indicator has a qualitative manner and can be evaluated in three options: “high”, “medium” and “low”. Social acceptability scores are based on a survey conducted in İstanbul (Erbil, 2011). The scores are also compared with the previously published paper which examines the social acceptability levels of different energy sources (Maxim, 2014). The scores are overlapping for all technologies except hydropower. Due to the public reaction of hydropower technologies including both with dam and run-of-river, social acceptability scores are considered as “low”. The benefit attribution of this indicator is positive; the higher the social acceptability, the better is the score. For this reason, technologies with high acceptability scores have the highest score, 1; while technologies with low acceptability have a score of zero (**Table 3.10**).

Table 3.10 Evaluation of the social acceptability scores

Technology	Social acceptability	Normalized
Coal	low	0
Natural gas	medium	0.5
Solar PV	high	1
Hydro (dam)	low	0
Hydro (run-of-river)	low	0
Wind (onshore)	high	1

3.2.1.11 Accident-related fatality

The third socio-economic indicator is accident-related fatality expressed in fatalities per GWh. Although fatality scores differ in each country, and required to be evaluated with country-based calculations; Turkey-specific statistics are not available for existing technology types. For this reason, accident-related fatality scores are taken as the nominal values per GWh (Klein and Whalley, 2015) based on the fatality data suggested for Organization for Economic Cooperation and Development (OECD) countries. The fatality data is gathered from Intergovernmental Panel on Climate Change report (IPCC, 2012) which uses the Energy-related Severe Accident Database (ENSAD) at Paul Scherrer Institut (PSI) considering severe (≥5 fatalities) accidents. The highest fatality rates are calculated for coal power plants, followed by natural gas.

Generally, renewable technologies have lower fatality scores compared to fossil fuel technologies (**Table 3.11**).

Table 3.11 Evaluation of the accident-related fatality scores

Technology	Accident-related fatality, ratesxE7/GWh	Normalized
Coal	170	0.0
Natural gas	94	0.5
Solar PV	1.3	1.0
Hydro (dam)	58	0.7
Hydro (run-of-river)	58	0.7
Wind (onshore)	5.2	1.0

3.2.1.12 Primary energy and technology dependence

The last socio-economic indicator is primary energy and technology dependence considering both source and technology-based imports. Primary energy dependence scores for Turkey are gathered from the online database which shows the imported resource necessities for each country (Eurostat, 2013). In addition to resources, import dependency of power plant technologies is also scored with respect to the expert opinion. This indicator has a qualitative manner and can be evaluated in three options: “high”, “medium” and “low”. Natural gas has the highest score due to its both source and technology dependency. Renewable technologies like solar PV and wind are also quite import dependent from technological point of view even their source is available naturally. Coal power plants have moderate scores while run-of-river and hydropower with dam plants have the minimum import dependency. The benefit attribution of this indicator is negative; the lower the dependency, the better is the score. For this reason, technologies with high dependency scores have the lowest score zero; while technologies with low dependency have the score of 1 (**Table 3.12**).

Table 3.12 Evaluation of the primary energy and technology dependence scores

Technology	Supply security	Normalized
Coal	medium	0.5
Natural gas	high	0
Solar PV	high	0
Hydro (dam)	low	1
Hydro (run-of-river)	low	1
Wind (onshore)	high	0

The final set of indicators is depicted in **Table 3.13**. After the valuation of the indicators, normalization process is carried out as explained before in Section 2.3.3.

3.2.2 Calculation of the MCDA scores for different sensitivity cases

Once the set of sustainability indicators is assembled, weighting factors are to be considered for different preference scenarios as shown in **Figure 2.8**. Since there is only one economic indicator, LCOE indicator weight is considered equal to the criteria group value. However, as seen in the socio-economic indicators, criteria groups with more than one indicator have evenly distributed weights.

Final step of the methodology is to determine the preference orders of the alternative electricity generation options according to their corresponding weights. Weighted sum method (WSM) is the most commonly used approach in sustainable energy systems decision-making. Normalized scores and weighting factors are gathered to reach the final MCDA scores. The final MCDA scores are given in **Figure 3.90**.

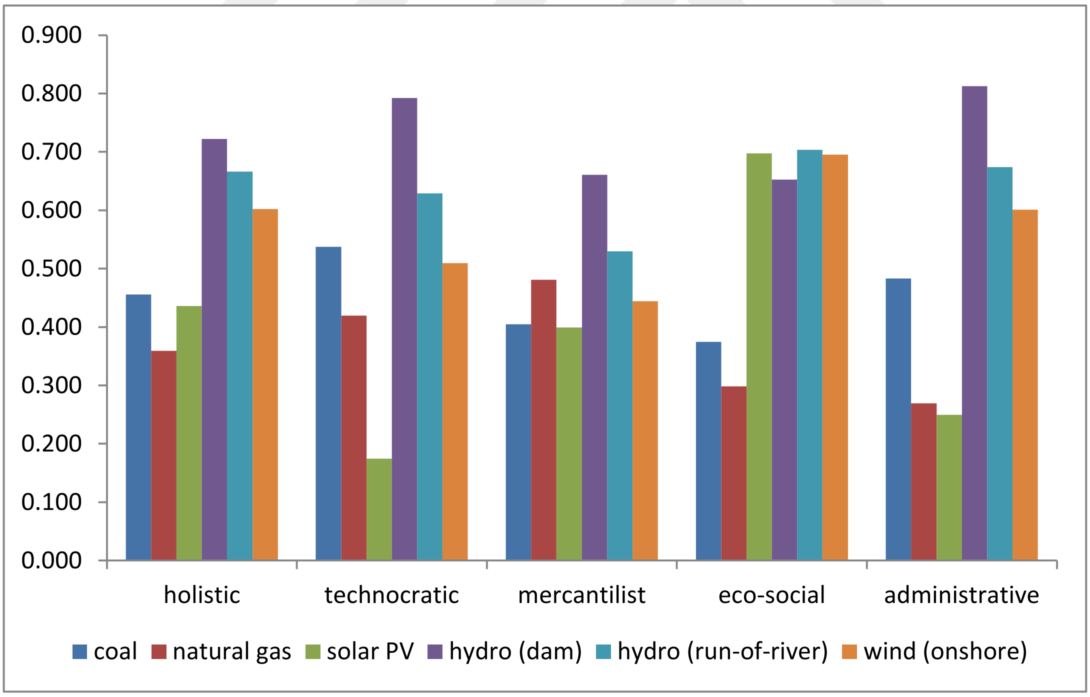


Figure 3.90 MCDA scores of the different sensitivity cases

According to the scores of each alternative generation technology, it is possible to make a priority ranking to assist decision-making process from a sustainable point of view.

Table 3.13 Sustainability indicators for each electricity generation technology

Generation technology	Unit	Natural Gas	Coal	Hydro (dam)	Hydro (r-o-r)	Wind (onshore)	Solar PV
LCOE	USD/MWh	156	92.5	41	65	73	160[a]
Efficiency	%	52	38	78	82	35[b]	16 [b]
Flexibility[c]	Qualitative	Yes, rapid	Yes, slow	Yes, rapid	No	No	No
Electricity mix share	%	47.9	30.2	11.3	4.8	3.4	0.01
Capacity factor	%	85[b]	85[b]	54	54	38	18
Climate change[d]	g CO_2-eq/kWh	482	1192	50	11	0.1	3.6
Ozone depletion[d]	g CFC 11-eq/GWh	67.7	4.2	0.5	0.9	0.03	0.7
Natural land transformation[d]	m^2/GWh	70.3	36.3	92.3	1.17	0.06	0.51
Job creation[e]	job-yrs./GWh	0.11	0.11	0.55	0.27	0.17	0.87
Social acceptability[c]	Qualitative	Medium	Low	Low	Low	High	High
Accident-related fatality[f]	Rate x 10^7/GWh	94	170	58	58	5.2	1.3
Primary energy and technology dependence[c]	Qualitative	High	Medium	Low	Low	High	High

[a] European average; [b] Average value of a standard technology; [c] Expert judgement; [d] Own calculation based on ecoinvent database; [e] World average; [f] OECD average

3.2.3 Ranking of the electricity generation technologies

Due to the nature of the WSM, the highest score indicates the best alternative among other generation technologies. Yet, as seen in **Table 3.14**, different sensitivity cases result in different rankings of the MCDA scores. This underlines the need for sensitivity analysis in decision making process rather than just one preference scenario.

Table 3.14 Ranking of the MCDA scores according to the different sensitivity cases

	Holistic	Technocratic	Mercantilist	Eco-social	Administrative
1	Hydro (dam)	Hydro (dam)	Hydro (dam)	Hydro (r-o-r)	Hydro (dam)
2	Hydro (r-o-r)	Hydro (r-o-r)	Hydro (r-o-r)	Solar PV	Hydro (r-o-r)
3	Wind (onshore)	Coal	Natural gas	Wind (onshore)	Wind (onshore)
4	Coal	Wind (onshore)	Wind (onshore)	Hydro (dam)	Coal
5	Solar PV	Natural gas	Coal	Coal	Natural gas
6	Natural gas	Solar PV	Solar PV	Natural gas	Solar PV

Even the results of the MCDA reveal that the hydropower technology with dam is the best for four out of five sensitivity cases; the evaluation considers average performance of a hydropower unit with dam anywhere across the country. The location of the dam is the most crucial decision in power plant design since it may ruin the fertile agricultural land and/or destroy the cultural and social texture. The opportunity cost of power plant implementation should be cautiously analyzed. Accordingly, site-specific analysis may change the ranking due to the geographic and socio-cultural characteristics of the power plant farm. Despite the possible drawbacks, hydropower is still one of the most important electricity generation alternatives since its high natural potential as well as economic and technical advantages.

The second best sustainable technology is run-of-river hydropower plant. Similar to hydropower with dam technologies, run-of-river power plant potential is quite high for Turkey. If the policy implementations cooperate with agricultural irrigation, this technology gets quite advantageous financially and also gains support of the social community.

Onshore wind power plants have reasonably high scores for each case. The potential electricity generation capacity from wind for Turkey is quite high due to its geographic location. Renewable energy alternatives are the key to fossil fuel dependency problem especially for leading energy importing countries. Therefore, wind technology has gradually increasing generation shares over the last years even the current levels cannot compete with the actual generation potential.

Coal technology has moderate scores and it has one third of the total production share in 2014. From sustainable point of view, fossil fuels are no longer an option for future generations owing to its environmental and socio-economic criteria scores. Environmental burdens resulting from fossil fuel technologies are the main contributors to global warming problem. From socio-economic view, high scores of accident-related fatality create a serious issue for occupational health and safety considerations but these technologies are preferred extensively for their low fuel costs.

Natural gas has low scores in most sensitivity cases. Despite having the biggest share in the generation mix, natural gas technology has some serious drawbacks from environmental and socio-economic point of view. Almost all of the natural gas used is imported from different countries and it results in a very high score of import dependency. For a sustainable energy decision making, new investments on natural gas technology may not be a practical alternative to offer. However, the advantage of fast response to urgent energy needs, natural gas power plants cannot be shut down. Their generation share should be kept under control in agreement with sustainable options.

Solar PV is a promising generation technology but it has the lowest scores for most cases owing to its high financial costs as well as high import dependency and low flexibility. As the sustainability notion and source diversification needs emerge, solar technology shares start to increase recently. Also, costs of solar PV technologies tend to decrease with the rapid technological developments. So, solar PV technology share is expected to increase progressively as the reputation of renewable technologies grows.

3.2.4 Comparison of the MCDA results with literature

According to the computations of different sensitivity cases, sustainability ranking of the generation technologies may be concluded as hydropower with dam, run-of-river hydropower, onshore wind, coal, natural gas, and solar PV. There are various studies discussed below agreeing to some extent with the results of this study.

Boran et al. (2013, 2017) examine the main energy sources for electricity generation and suggest a ranking of hydro, wind, gas, fossil fuels, and geothermal power plants. Atilgan and Azapagic (2016) investigate the current electricity generation options and suggest that the most sustainable technology is hydro followed by geothermal and wind for different preferences. Özkale et al. (2017) consider the power plants running on renewable energy resource and conclude that hydroelectricity takes the first place according to the general results followed by solar, wind, biomass and finally geothermal. Şengül et al. (2015) analyse renewable energy options and their analysis shows that the hydro power station is the most renewable energy supply system in Turkey. Additionally, the geothermal power station, regulator and wind power station are determined to be the second, third and fourth, respectively. Balin and Baraçlı (2015) examine the renewable energy alternatives and report that wind is the best alternative for Turkey’s energy investments, as being followed subsequently by solar, biomass, geothermal, hydraulic and hydrogen. Büyüközkan and Güleryüz (2017) develop an evaluation model to select the most appropriate renewable energy resource in Turkey and conclude that the best renewable energy technology is power generation from geothermal sources, followed by biogas. Çelikbilek and Tüysüz (2016) present a grey based multi-criteria decision model for the evaluation of renewable energy sources and discuss that the ranking is as follows solar, wind, hydro, biomass and geothermal. Kahraman et al. (2009) apply fuzzy axiomatic design to the selection of the best renewable energy alternative and mention that the ranking is as wind, solar, biomass, geothermal, and hydropower.

One of the main reasons for the difference in the ranking of alternative technologies is the data acquisition perspective of the studies since it is not always possible to find country-specific data. Reported indicator values show a very wide range of change even for the same technology and cause uncertainties for the results. However, this is an inevitable consequence of the studies of such broad scope. In order to avoid the uncertainties, a representative power plant of each generation technology may be selected and evaluated with site-specific data in terms of indicators. But, of course, this is a very time-consuming mission for depicting country-wide electricity generation profile.

The other possible reasons for the difference in the ranking are assumptions in the generation technologies, selection principles of indicators, numeric or linguistic evaluation of the indicators, selection of the normalization method, preferences in the weighting, and also selection of the MCDA method to get the total sustainability scores. In a very broad perspective, all of the literature researches including our study show that fossil fuel technologies are not viable options from a sustainable point of view and renewable technologies are to be employed in the future generation technologies.

4 CONCLUSIONS

Electricity generation is the main driving force of industrial processes in a country, and consequently, the generation activities play essential role in planning the future strategies of a country. In order to propose sustainable future scenarios, first, current generation profile of Turkey is analysed comprehensively. For this aim, LCA methodology is applied for 2014 generation mix with different impact assessment methods. Single issue impact assessment methods are easy to apply but their results may leave out impact categories that have a significant impact due to their limited scope. Nevertheless, single issue methods can be used for drawing a general perspective about the generation alternatives. In order to fully understand the environmental impacts associated with the generation alternatives multiple issue methods are required. Multiple issue impact assessment methods allow performing a comprehensive evaluation of related generation activities. Single issue impact assessment methods applied are IPCC 2013 GWP, CED, CExD while multiple issue impact assessment methods are CML 2 Baseline 2000 and ReCiPe (H) midpoint and ReCiPe (H) endpoint.

According IPCC 2013 GWP results almost all of the equivalent emissions of CO_2 are resulted from fossil fuels due to their high carbon content. CED and CExD scores are mainly evaluated in the category basis. Energy and exergy demand results are used for the future scenario comparisons. CML 2 Baseline 2000 results indicate that the environmental impacts are mainly caused by fossil fuel technologies. ReCiPe (H) midpoint results show similar tendencies with CML 2 baseline 2000 scores except three indicators; natural land transformation, water depletion and metal depletion. Mostly, all impacts are resulted from fossil fuel technologies while water depletion score is dominated by hydropower technologies. Natural land transformation and metal depletion scores are caused by hydropower technologies in addition to fossil fuels. ReCiPe (H) endpoint single scores indicate that the damage category scores are largely resulted from fossil fuel technologies. Only hydropower technologies have minor effect on ecosystems in addition to fossil fuels. As the analysis for 2014 indicates, fossil fuel technologies are the main sources of environmental impacts related to electricity generation activities. In order to decrease the environmental burdens, fossil fuel technologies should be substituted with renewable energy technologies for future scenarios.

As well as the current production activity evaluation, future scenarios are considered for the years 2023 and 2030 from sustainable point of view. Three different future scenarios are proposed as BAU, OP, and RDP. The same impact assessment methods are employed for the comparisons. According IPCC 2013 GWP method, scores for BAU and OP scenarios have increasing values for 2023 and 2030 projections due to their high fossil fuel shares. As seen in the results, GWP scores are kept close to 2014 levels only if the RDP strategy is put into practice. CED and CExD scores for future scenarios differ in the category basis. Non-renewable, fossil energy and exergy demand scores increase for BAU and OP scenarios while RDP scenario scores decrease even below 2014 levels. Non-renewable nuclear scores increase for each scenario since there is no operating plant in 2014. Renewable energy and exergy scores also increase for each scenario due to the higher shares of renewables in the future plans. CML 2 baseline 2000 scores indicate that BAU and OP impact scores are increasing in time compared to RDP scenario scores. ReCiPe (H) midpoint scores reveal that BAU and OP scenario impact scores are increasing in time while RDP scenario scores remain at -for some cases even fall below- 2014 levels. ReCiPe (H) endpoint single score results represent all of the LCA computation results and indicate that current levels can only be sustained if RDP scenario is put into practice.

The shift of the electricity mix towards more sustainable technologies is a vital necessity not only for Turkey but also for all the countries of the world. In order to propose a sustainable scenario, a comprehensive investigation is required not only from environmental point of view but also taking all possible aspects into consideration. There are numerous parameters for consideration and the applications may change due to the priorities of the decision-makers. In order to further analyse the LCA results for 2014, MCDA methodology is employed to make a ranking of the sustainability scores of generation technologies. MCDA scores are evaluated in four criteria groups and twelve indicators with respect to five different preference alternatives.

According to the MCDA ranking results, hydropower technologies are apparently the best option. The decision-makers should establish a policy about the efficient use of potential water resources with regard to sustainability. Renewable technologies like solar PV and wind have reasonably acceptable scores and increasing generation shares. From sustainable point of view, renewable energy sources should be fully operated. In addition to sustainability, strategical importance of renewable technologies should be taken into account, as well, in terms of supply security. In case of a natural disaster or political conflict, renewable energy technologies make it possible to generate electricity in local areas and give the opportunity to meet the demand as soon as it occurs. Fossil fuel technologies as coal and natural gas are still the driving force of electricity generation in Turkey, in 2014. Since natural gas power plants are considered as “emergency plants” due to their high flexibility; it is not possible to fully block their use but the limitations must be introduced considering the high import dependency and environmental impacts. Coal technology has serious environmental and socio-economic burdens but it is widely preferred for its low cost. Coal technology should also be regulated with respect to the sustainability aspects.

In order to choose the best option for country interests, comprehensive researches and realistic models are required. We hope this study gives a scientific and objective standpoint to decision-maker authorities in Turkey for planning sustainable electricity generation policies.

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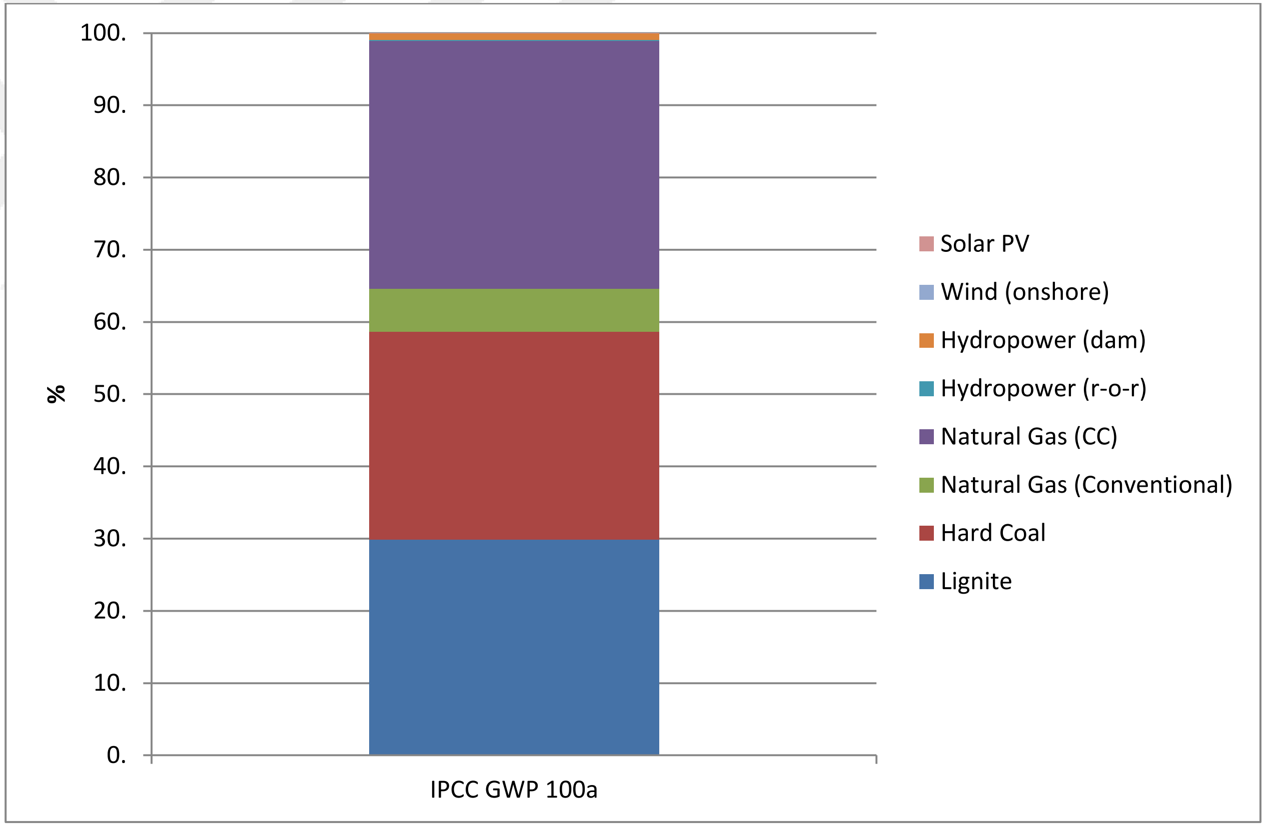
APPENDICES

A1. ASSUMPTIONS MADE IN LCA

- Since it is hard to find reliable country-specific decommissioning and waste disposal data, cradle-to-gate boundary is used.
- Average lifetime for fossil fuel power plants is estimated as 30 years.
- No transport process is needed for electricity production from lignite and domestic coal, since the power plants are constructed adjacent to mines.
- For imported coal data; Latin America & the Caribbean inventory is used for Columbia; North America inventory is used for USA and Canada; rest of the World (RoW) processes are used for Ukraine.
- Imported coal transport data are reorganized via online mapping. Imported coal tankers are assumed to be discharged in Istanbul.
- Transport from mine to port is ignored for imported coal. Coal is transported from port to port via tankers.
- Natural gas extracted from Turkey is ignored since it has very small share.
- Natural gas from Algeria and Nigeria is transported in LNG form via freight, sea, transoceanic tankers from port to port (Istanbul).
- Natural gas from Iran and Azerbaijan is transported via pipeline. The distance is calculated from source to Ankara.
- Natural gas from Russia is imported in two lines: the Blue Stream and the Western Line. Both distances are calculated from source to Ankara.
- Combined cycle power plant efficiency for natural gas is assumed to be 52% (52-61 %).
- Single cycle power plant efficiency for natural gas is assumed to be 38 % (35-42%).
- Natural gas pipeline life time is estimated as 40 years.
- Average lifetime for reservoir hydroelectric power plants is estimated as 80 years.
- Average lifetime for run-of-river hydroelectric power plants is estimated as 40 years.
- An average of 20 years of power plant lifetime estimated for wind and solar PV power plants.
- Solar PV efficiency is assumed to be 16%.
- Future projections are based on the installed power assumptions.

A2. COMPUTATION RESULTS FOR IPCC 2013 GWP IMPACT ASSESSMENT METHOD

Impact category	Unit	Lignite	Hard Coal	Natural Gas (Conventional)	Natural Gas (CC)	Hydropower (r-o-r)	Hydropower (dam)	Wind (onshore)	Solar PV
IPCC GWP 100a	kg CO_2 eq/kWh	1.27E+00	1.14E+00	7.59E-01	4.93E-01	1.14E-02	5.16E-02	9.32E-05	3.61E-03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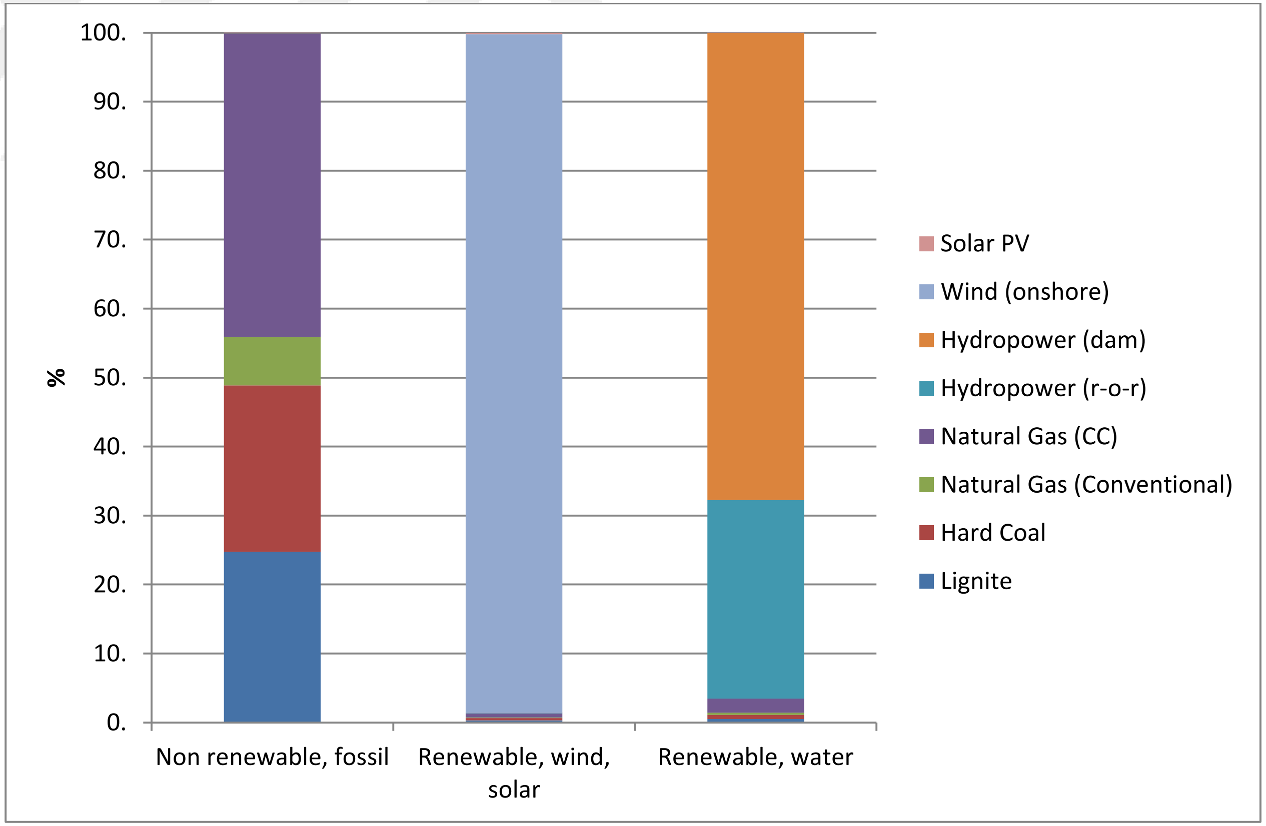
IPCC GWP 100a
Solar PV
Wind (onshore)
Hydropower (dam)
Hydropower (r-o-r)
Natural Gas (CC)
Natural Gas (Conventional)
Hard Coal
Lignite

A3. COMPUTATION RESULTS FOR CED IMPACT ASSESSMENT METHOD

Impact category	**Unit**	**Lignite**	**Hard Coal**	**Natural Gas (Conventional)**	**Natural Gas (CC)**	**Hydropower (r-o-r)**	**Hydropower (dam)**	**Wind (onshore)**	**Solar PV**
Non renewable, fossil	MJ/kWh	1.47E+01	1.32E+01	1.27E+01	8.76E+00	1.01E-01	5.65E-02	2.80E-03	4.13E-02
Renewable, wind, solar	MJ/kWh	3.03E-03	2.42E-03	2.80E-03	1.94E-03	4.99E-04	3.62E-04	3.87E+00	3.85E+00
Renewable, water	MJ/kWh	2.24E-02	2.37E-02	4.35E-02	3.01E-02	3.79E+00	3.79E+00	2.53E-05	6.27E-03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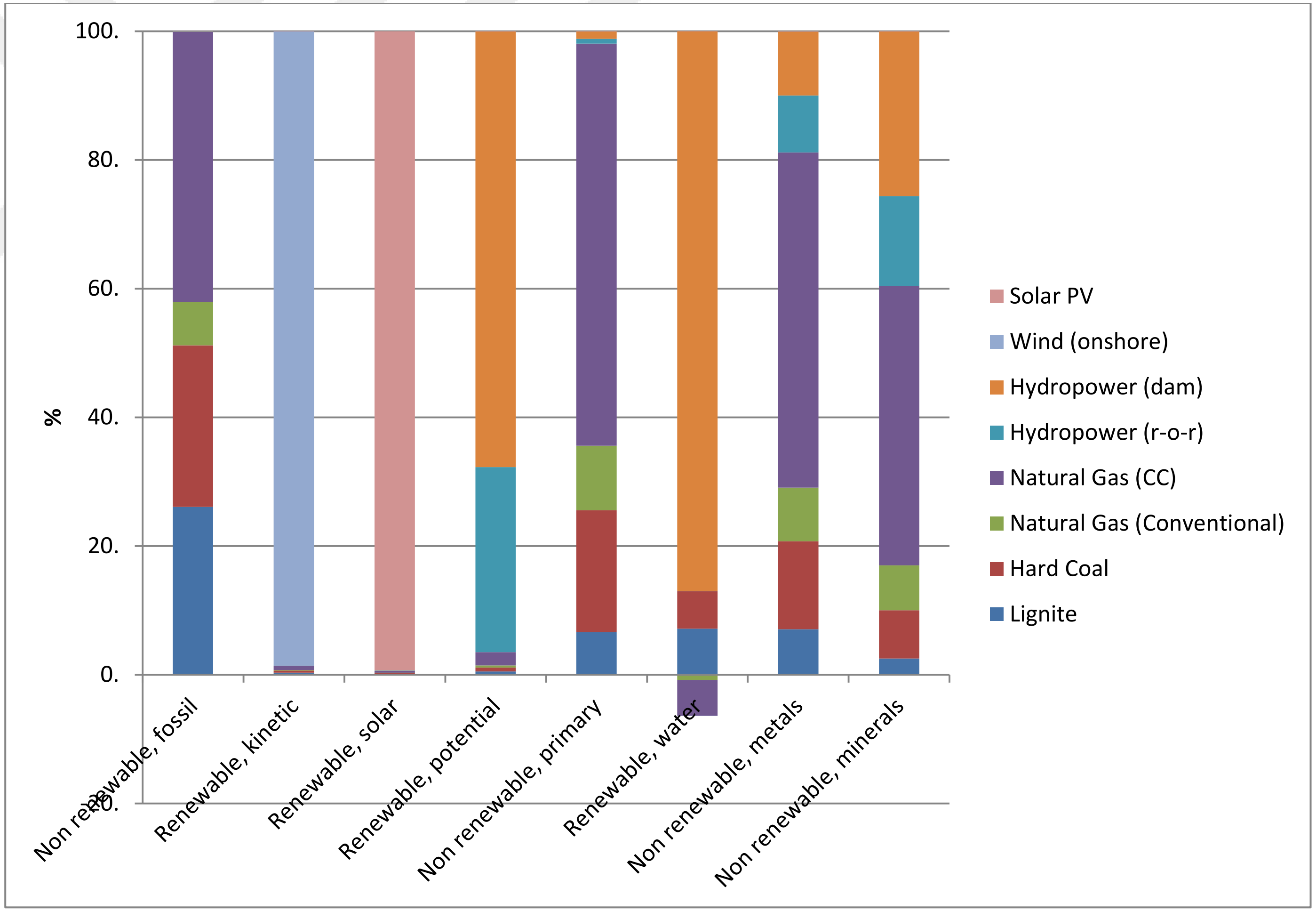
Non renewable, fossil
Renewable, wind, solar
Renewable, water
Solar PV
Wind (onshore)
Hydropower (dam)
Hydropower (r-o-r)
Natural Gas (CC)
Natural Gas (Conventional)
Hard Coal
Lignite

A4. COMPUTATION RESULTS FOR CExD IMPACT ASSESSMENT METHOD

Impact category	**Unit**	**Lignite**	**Hard Coal**	**Natural Gas (Conventional)**	**Natural Gas (CC)**	**Hydropower (r-o-r)**	**Hydropower (dam)**	**Wind (onshore)**	**Solar PV**
Non renewable, fossil	MJ/kWh	1.53E+01	1.36E+01	1.20E+01	8.26E+00	1.02E-01	5.71E-02	2.83E-03	4.14E-02
Renewable, kinetic	MJ/kWh	3.03E-03	2.41E-03	2.80E-03	1.94E-03	4.96E-04	3.60E-04	3.87E+00	3.79E-04
Renewable, solar	MJ/kWh	1.07E-06	3.59E-06	2.06E-06	1.42E-06	2.44E-06	1.52E-06	2.75E-08	3.58E+00
Renewable, potential	MJ/kWh	2.24E-02	2.37E-02	4.35E-02	3.01E-02	3.79E+00	3.79E+00	2.53E-05	6.27E-03
Non renewable, primary	MJ/kWh	9.38E-06	2.50E-05	4.33E-05	2.99E-05	3.26E-06	2.14E-06	9.61E-08	7.11E-06
Renewable, water	MJ/kWh	9.38E-02	7.01E-02	-3.22E-02	-2.46E-02	2.20E-03	1.46E+00	-1.30E-05	2.18E-03
Non renewable, metals	MJ/kWh	3.23E-03	5.79E-03	1.16E-02	8.04E-03	1.22E-02	5.85E-03	1.05E-04	2.29E-03
Non renewable, minerals	MJ/kWh	2.74E-04	7.59E-04	2.32E-03	1.60E-03	4.63E-03	3.60E-03	6.24E-06	9.08E-05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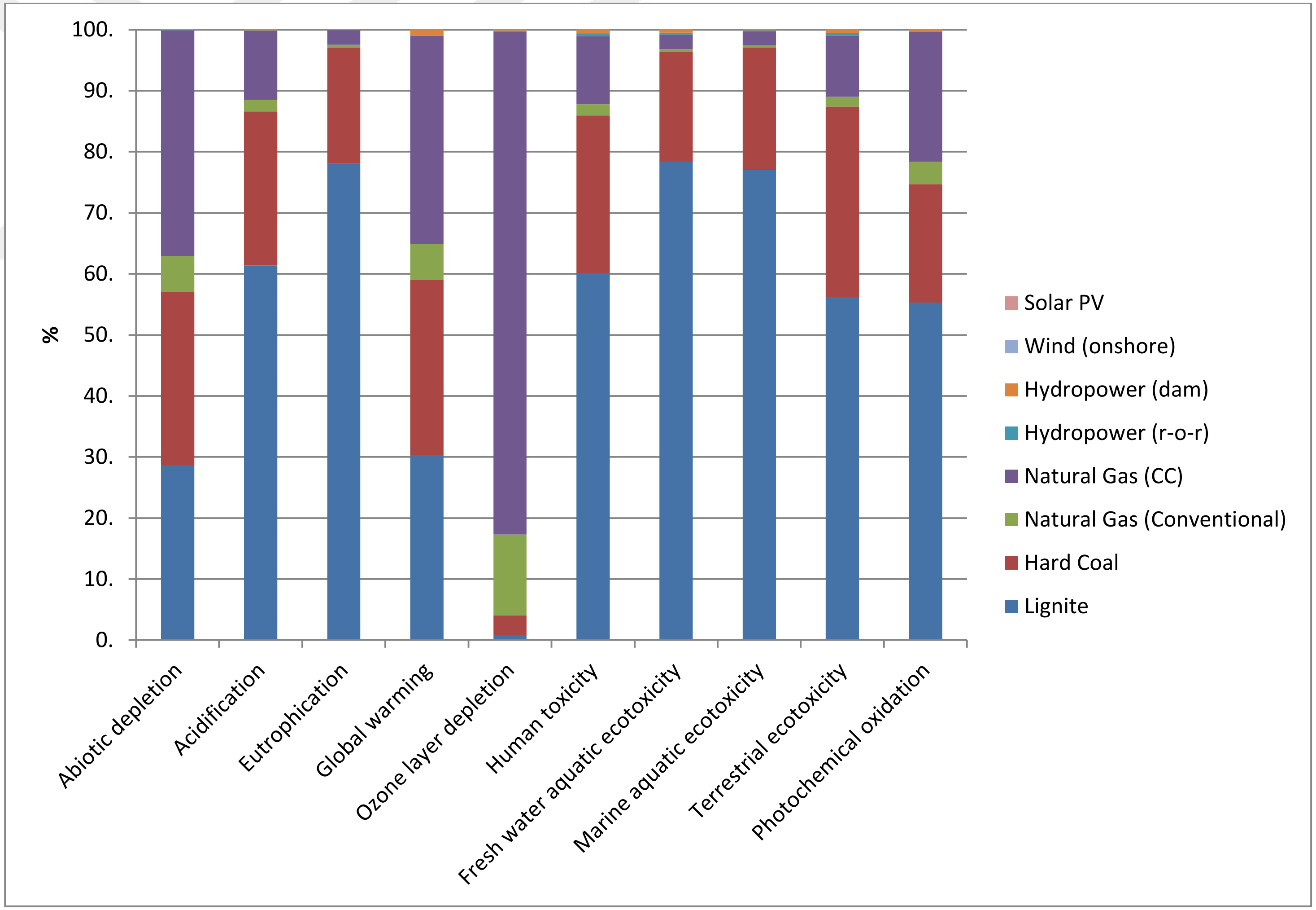
Non renewable, fossil
Renewable, kinetic
Renewable, solar
Renewable, potential
Non renewable, primary
Renewable, water
Non renewable, metals
Non renewable, minerals
Solar PV
Wind (onshore)
Hydropower (dam)
Hydropower (r-o-r)
Natural Gas (CC)
Natural Gas (Conventional)
Hard Coal
Lignite

A5. COMPUTATION RESULTS FOR CML 2 BASELINE 2000 IMPACT ASSESSMENT METHOD

Impact category	Unit	Lignite	Hard Coal	Natural Gas (Conventional)	Natural Gas (CC)	Hydropower (r-o-r)	Hydropower (dam)	Wind (onshore)	Solar PV
Abiotic depletion	kg Sb eq/kWh	9.93E-03	9.10E-03	6.25E-03	4.32E-03	5.49E-05	3.07E-05	1.30E-06	2.45E-05
Acidification	kg SO_2 eq/kWh	1.27E-02	4.82E-03	1.21E-03	7.86E-04	4.63E-05	2.57E-05	5.31E-07	2.12E-05
Eutrophication	kg PO_4^{3-} eq/kWh	1.09E-02	2.45E-03	1.81E-04	1.12E-04	1.82E-05	8.73E-06	2.03E-07	8.71E-06
Global warming	kg CO_2 eq/kWh	1.27E+00	1.11E+00	7.42E-01	4.81E-01	1.13E-02	5.00E-02	9.21E-05	3.53E-03
Ozone layer depletion	kg CFC-11 eq/kWh	1.72E-09	6.29E-09	8.40E-08	5.80E-08	8.30E-10	4.59E-10	3.29E-11	6.50E-10
Human toxicity	kg 1,4-DB eq/kWh	9.04E-01	3.60E-01	8.58E-02	5.65E-02	2.02E-02	1.15E-02	1.51E-04	5.60E-03
Fresh water aquatic ecotoxicity	kg 1,4-DB eq/kWh	1.59E+00	3.39E-01	2.32E-02	1.60E-02	2.10E-02	1.27E-02	3.68E-04	4.32E-03
Marine aquatic ecotoxicity	kg 1,4-DB eq/kWh	3.23E+03	7.76E+02	4.76E+01	3.29E+01	1.32E+01	7.06E+00	1.79E-01	4.86E+00
Terrestrial ecotoxicity	kg 1,4-DB eq/kWh	2.67E-03	1.37E-03	2.32E-04	1.59E-04	7.04E-05	3.29E-05	5.26E-07	1.61E-05

Impact category	**Unit**	**Lignite**	**Hard Coal**	**Natural Gas (Conventional)**	**Natural Gas (CC)**	**Hydropower (r-o-r)**	**Hydropower (dam)**	**Wind (onshore)**	**Solar PV**
Photochemical oxidation	kg C_2H_4 eq/kWh	4.62E-04	1.50E-04	9.31E-05	5.98E-05	2.80E-06	2.56E-06	3.03E-08	1.15E-06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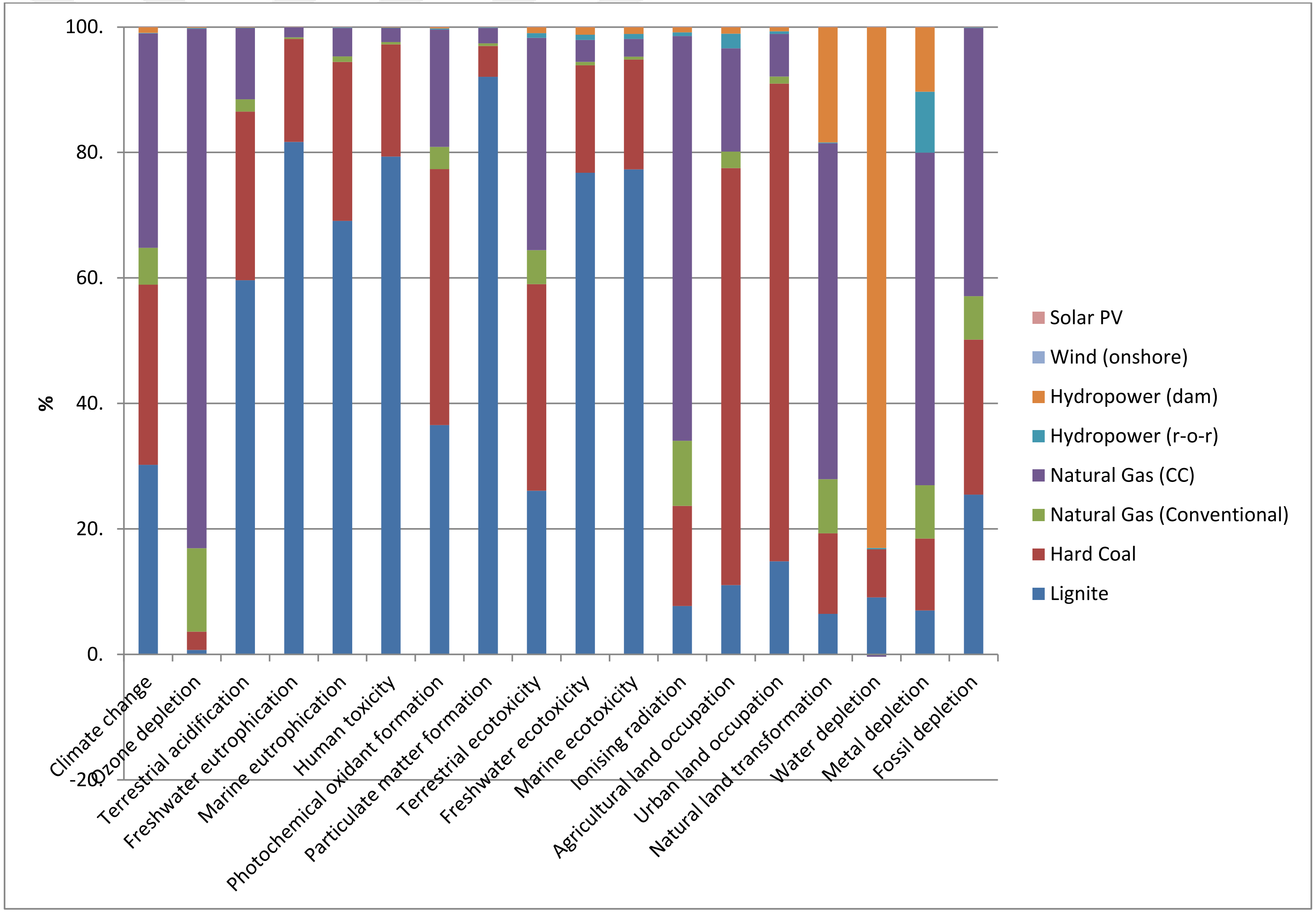
Abiotic depletion
Acidification
Eutrophication
Global warming
Ozone layer depletion
Human toxicity
Fresh water aquatic ecotoxicity
Marine aquatic ecotoxicity
Terrestrial ecotoxicity
Photochemical oxidation
Solar PV
Wind (onshore)
Hydropower (dam)
Hydropower (r-o-r)
Natural Gas (CC)
Natural Gas (Conventional)
Hard Coal
Lignite

A6. COMPUTATION RESULTS FOR ReCiPe (H) MIDPOINT IMPACT ASSESSMENT METHOD

Impact category	**Unit**	**Lignite**	**Hard Coal**	**Natural Gas (Conventional)**	**Natural Gas (CC)**	**Hydropower (r-o-r)**	**Hydropower (dam)**	**Wind (onshore)**	**Solar PV**
Climate change	kg CO_2 eq/kWh	1.27E+00	1.12E+00	7.46E-01	4.84E-01	1.13E-02	5.04E-02	9.22E-05	3.55E-03
Ozone depletion	kg CFC-11 eq/kWh	1.80E-09	6.48E-09	9.83E-08	6.79E-08	8.63E-10	4.75E-10	3.39E-11	6.95E-10
Terrestrial acidification	kg SO_2 eq/kWh	1.10E-02	4.57E-03	1.10E-03	7.02E-04	4.46E-05	2.46E-05	4.72E-07	1.92E-05
Freshwater eutrophication	kg P eq/kWh	3.38E-03	6.28E-04	3.17E-05	2.19E-05	4.05E-06	1.87E-06	5.17E-08	2.30E-06
Marine eutrophication	kg N eq/kWh	8.18E-04	2.77E-04	3.18E-05	1.81E-05	2.29E-06	1.20E-06	2.04E-08	1.39E-06
Human toxicity	kg 1,4-DB eq/kWh	1.93E+00	4.02E-01	2.63E-02	1.81E-02	6.77E-03	3.24E-03	9.27E-05	3.37E-03
Photochemical oxidant formation	kg NMVOC/ kWh	3.67E-03	3.79E-03	1.07E-03	6.34E-04	5.10E-05	2.73E-05	6.10E-07	1.36E-05
Particulate matter formation	kg PM10 eq/kWh	2.81E-02	1.39E-03	4.01E-04	2.55E-04	6.14E-05	2.34E-05	2.02E-07	1.05E-05

Impact category	**Unit**	**Lignite**	**Hard Coal**	**Natural Gas (Conventional)**	**Natural Gas (CC)**	**Hydropower (r-o-r)**	**Hydropower (dam)**	**Wind (onshore)**	**Solar PV**
Terrestrial ecotoxicity	kg 1,4-DB eq/kWh	1.17E-05	1.36E-05	7.40E-06	5.10E-06	9.77E-07	5.68E-07	9.96E-09	6.33E-06
Freshwater ecotoxicity	kg 1,4-DB eq/kWh	4.73E-02	9.73E-03	1.05E-03	7.26E-04	1.54E-03	9.52E-04	3.40E-05	2.86E-04
Marine ecotoxicity	kg 1,4-DB eq/kWh	4.53E-02	9.48E-03	8.08E-04	5.58E-04	1.35E-03	8.35E-04	2.94E-05	2.70E-04
Ionising radiation	kBq U235 eq/kWh	3.46E-03	6.58E-03	1.40E-02	9.70E-03	7.57E-04	4.92E-04	1.43E-05	3.98E-04
Agricultural land occupation	m^{2}a/kWh	1.51E-03	8.40E-03	1.09E-03	7.57E-04	9.60E-04	1.85E-04	2.62E-06	2.62E-04
Urban land occupation	m^{2}a/kWh	1.77E-03	8.40E-03	3.96E-04	2.73E-04	1.62E-04	1.02E-04	1.37E-06	1.24E-03
Natural land transformation	m^2/kWh	2.53E-05	4.64E-05	1.02E-04	7.05E-05	1.17E-06	9.24E-05	6.48E-08	5.14E-07
Water depletion	m^3/kWh	2.51E-03	1.94E-03	1.81E-05	-3.43E-05	1.65E-04	2.93E-02	8.55E-07	1.37E-04
Metal depletion	kg Fe eq/kWh	1.28E-03	1.93E-03	4.69E-03	3.25E-03	5.35E-03	2.41E-03	2.52E-05	7.10E-04
Fossil depletion	kg oil eq/kWh	3.34E-01	2.99E-01	2.73E-01	1.89E-01	2.28E-03	1.27E-03	6.32E-05	9.22E-04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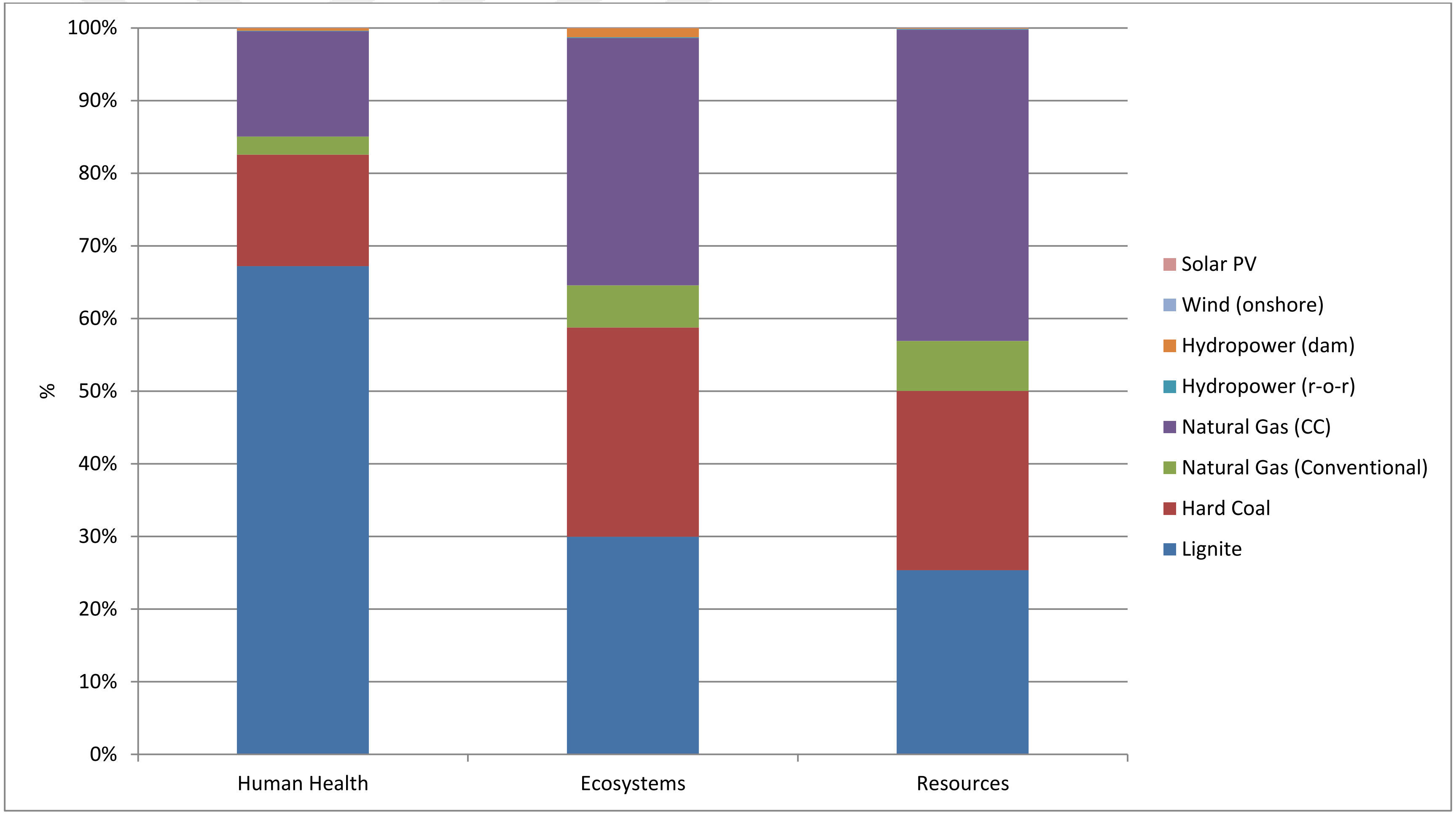
Climate change
Ozone depletion
Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Human toxicity
Photochemical oxidant formation
Particulate matter formation
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Ionising radiation
Agricultural land occupation
Urban land occupation
Natural land transformation
Water depletion
Metal depletion
Fossil depletion
Solar PV
Wind (onshore)
Hydropower (dam)
Hydropower (r-o-r)
Natural Gas (CC)
Natural Gas (Conventional)
Hard Coal
Lignite

A7. COMPUTATION RESULTS FOR ReCiPe (H) ENDPOINT IMPACT ASSESSMENT METHOD

Damage category	**Unit**	**Total**	**Lignite**	**Hard Coal**	**Natural Gas (Conventional)**	**Natural Gas (CC)**	**Hydropower (r-o-r)**	**Hydropower (dam)**	**Wind (onshore)**	**Solar PV**
Human Health	GPt	1.13E+01	7.56E+00	1.73E+00	2.79E-01	1.63E+00	8.74E-03	4.45E-02	4.19E-05	3.46E-06
Ecosystems	GPt	2.82E+00	8.45E-01	8.11E-01	1.64E-01	9.59E-01	2.90E-03	3.65E-02	1.79E-05	2.29E-06
Resources	GPt	5.16E+00	1.31E+00	1.27E+00	3.55E-01	2.21E+00	5.95E-03	7.05E-03	6.80E-05	2.29E-06


100%
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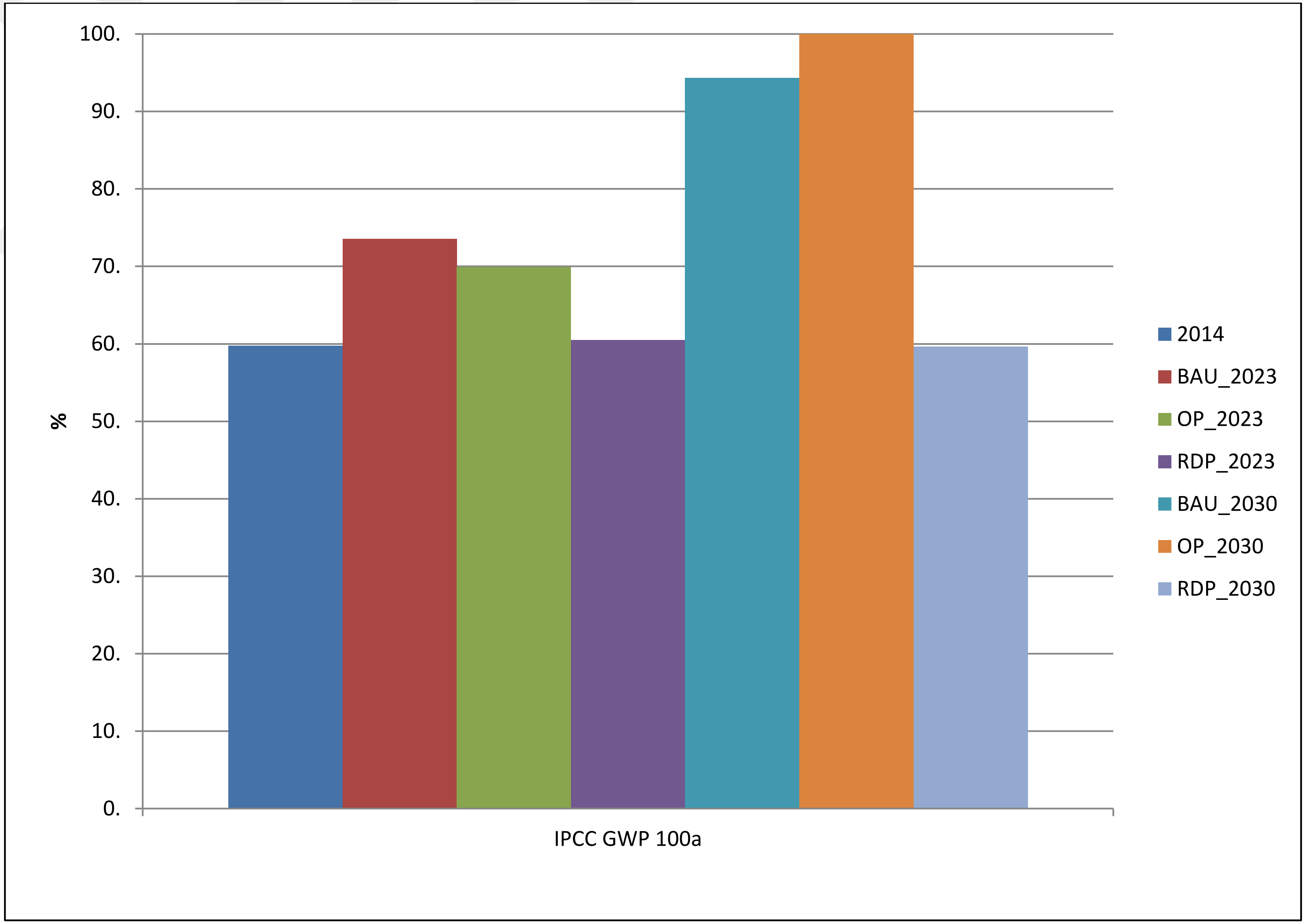
%
Human Health
Ecosystems
Resources
Solar PV
Wind (onshore)
Hydropower (dam)
Hydropower (r-o-r)
Natural Gas (CC)
Natural Gas (Conventional)
Hard Coal
Lignite

A8. COMPARISON OF FUTURE SCENARIOS WITH IPCC 2013 GWP IMPACT ASSESSMENT METHOD

Impact category	Unit	2014	BAU_2023	OP_2023	RDP_2023	BAU_2030	OP_2030	RDP_2030
IPCC GWP 100a	kg CO_2 eq	1.56E+11	1.92E+11	1.82E+11	1.58E+11	2.46E+11	2.61E+11	1.56E+11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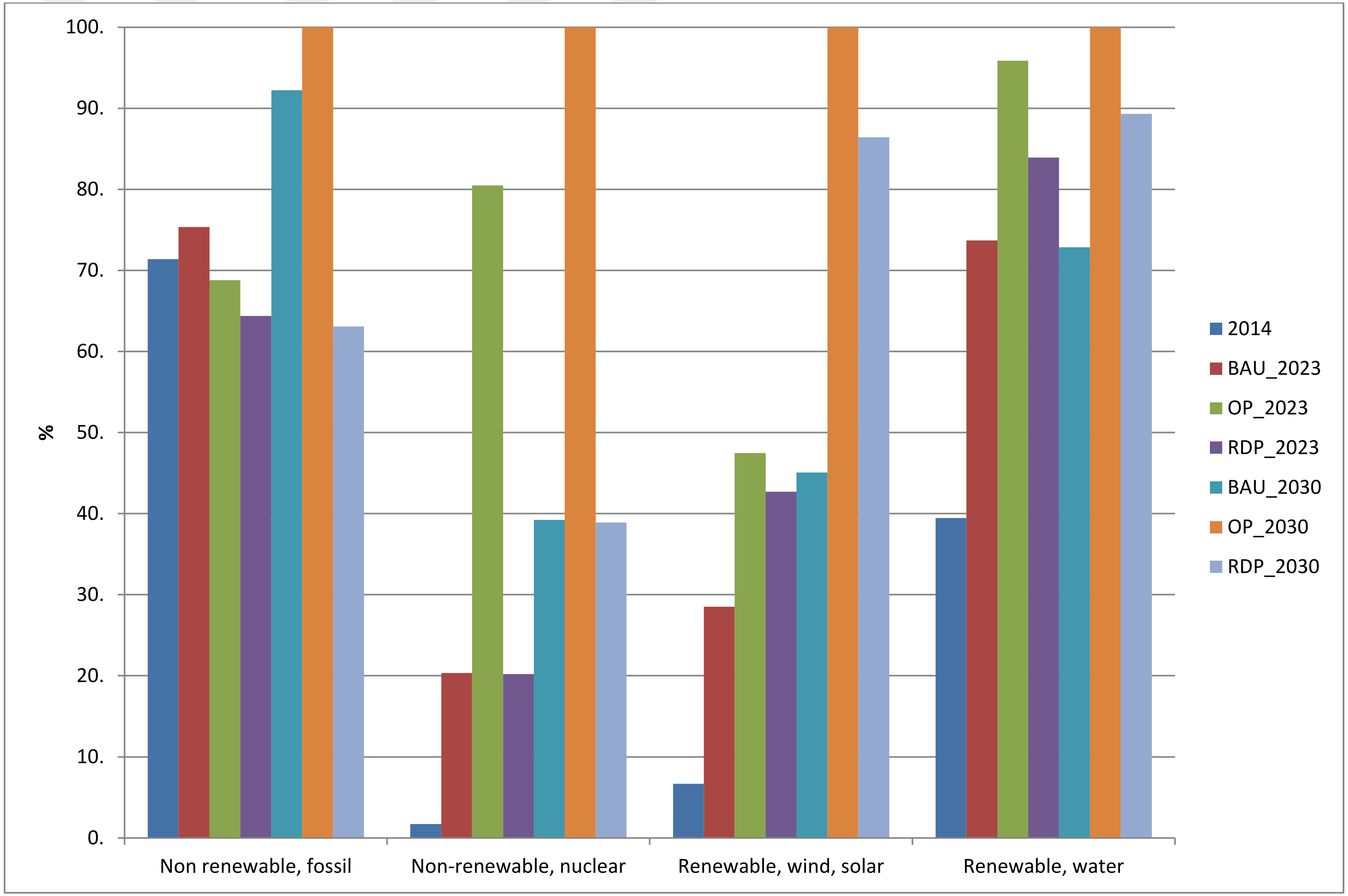
IPCC GWP 100a
2014
BAU_2023
OP_2023
RDP_2023
BAU_2030
OP_2030
RDP_2030

A9. COMPARISON OF FUTURE SCENARIOS WITH CED IMPACT ASSESSMENT METHOD

Impact category	**Unit**	**2014**	**BAU_2023**	**OP_2023**	**RDP_2023**	**BAU_2030**	**OP_2030**	**RDP_2030**
Non-renewable, fossil	MJ	2.17E+12	2.29E+12	2.09E+12	1.95E+12	2.80E+12	3.03E+12	1.91E+12
Non-renewable, nuclear	MJ	2.24E+10	2.65E+11	1.05E+12	2.63E+11	5.11E+11	1.30E+12	5.07E+11
Renewable, wind, solar	MJ	3.37E+10	1.44E+11	2.39E+11	2.15E+11	2.27E+11	5.03E+11	4.35E+11
Renewable, water	MJ	1.59E+11	2.98E+11	3.87E+11	3.39E+11	2.95E+11	4.04E+11	3.61E+11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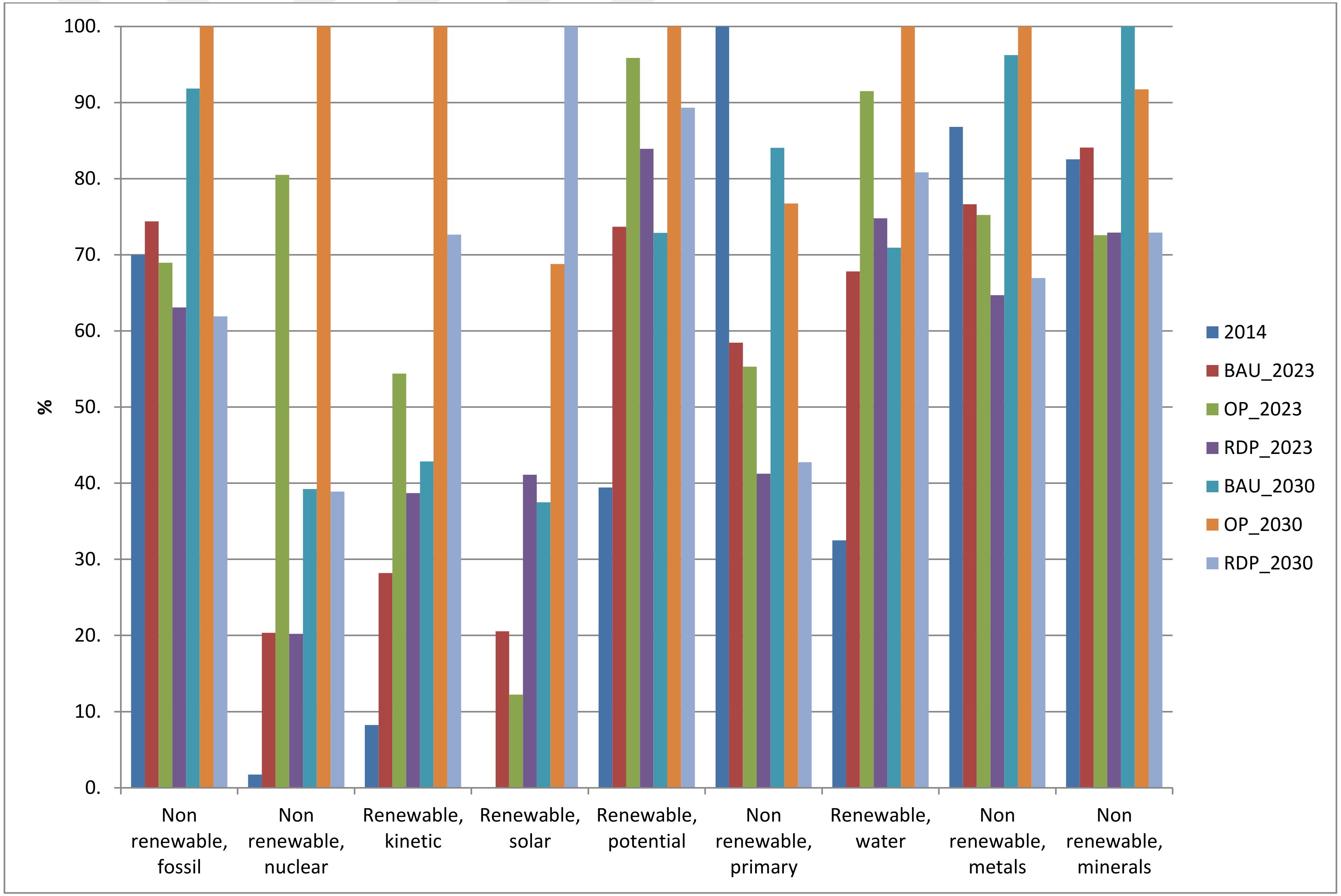
Non renewable, fossil
Non-renewable, nuclear
Renewable, wind, solar
Renewable, water
2014
BAU_2023
OP_2023
RDP_2023
BAU_2030
OP_2030
RDP_2030

A10. COMPARISON OF FUTURE SCENARIOS WITH CExD IMPACT ASSESSMENT METHOD

Impact category	**Unit**	**2014**	**BAU_2023**	**OP_2023**	**RDP_2023**	**BAU_2030**	**OP_2030**	**RDP_2030**
Non renewable, fossil	MJ	2.14E+12	2.27E+12	2.11E+12	1.93E+12	2.81E+12	3.06E+12	1.89E+12
Non renewable, nuclear	MJ	2.24E+10	2.65E+11	1.05E+12	2.63E+11	5.11E+11	1.30E+12	5.07E+11
Renewable, kinetic	MJ	3.36E+10	1.15E+11	2.22E+11	1.58E+11	1.75E+11	4.08E+11	2.96E+11
Renewable, solar	MJ	6.27E+07	2.65E+10	1.58E+10	5.30E+10	4.83E+10	8.87E+10	1.29E+11
Renewable, potential	MJ	1.59E+11	2.98E+11	3.87E+11	3.39E+11	2.95E+11	4.04E+11	3.61E+11
Non renewable, primary	MJ	5.21E+06	3.04E+06	2.88E+06	2.15E+06	4.38E+06	4.00E+06	2.23E+06
Renewable, water	MJ	4.47E+10	9.34E+10	1.26E+11	1.03E+11	9.77E+10	1.38E+11	1.11E+11
Non renewable, metals	MJ	1.68E+09	1.48E+09	1.45E+09	1.25E+09	1.86E+09	1.93E+09	1.29E+09
Non renewable, minerals	MJ	4.00E+08	4.08E+08	3.52E+08	3.54E+08	4.85E+08	4.45E+08	3.54E+08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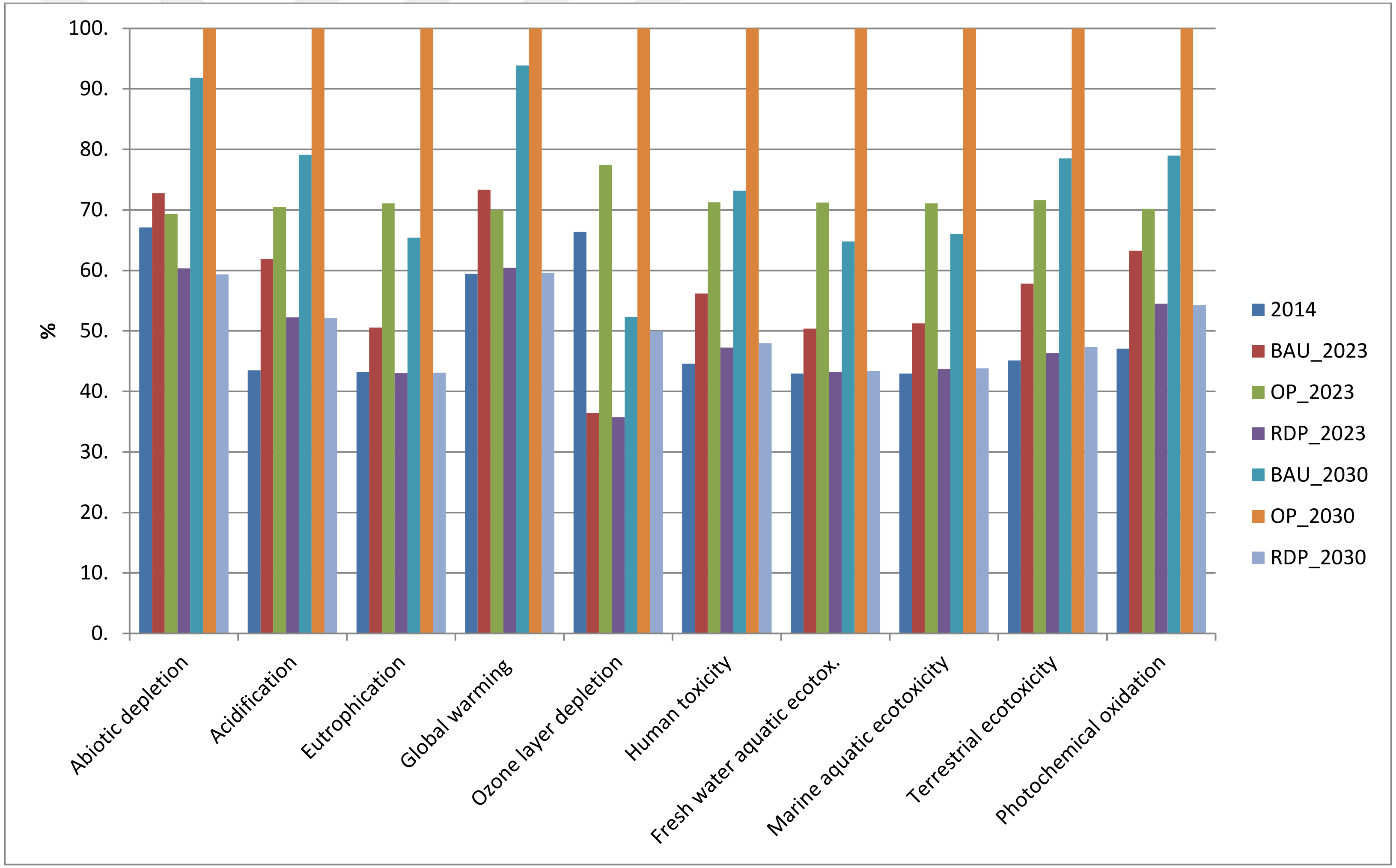
Non renewable, fossil
Non renewable, nuclear
Renewable, kinetic
Renewable, solar
Renewable, potential
Non renewable, primary
Renewable, water
Non renewable, metals
Non renewable, minerals
2014
BAU_2023
OP_2023
RDP_2023
BAU_2030
OP_2030
RDP_2030

A11. COMPARISON OF FUTURE SCENARIOS WITH CML 2 BASELINE 2000 IMPACT ASSESSMENT METHOD

Impact category	Unit	2014	BAU_2023	OP_2023	RDP_2023	BAU_2030	OP_2030	RDP_2030
Abiotic depletion	kg Sb eq	1.27E+09	1.38E+09	1.31E+09	1.14E+09	1.74E+09	1.89E+09	1.12E+09
Acidification	kg SO2 eq	7.55E+08	1.07E+09	1.22E+09	9.07E+08	1.37E+09	1.74E+09	9.05E+08
Eutrophication	kg PO4--- eq	5.11E+08	5.98E+08	8.41E+08	5.09E+08	7.73E+08	1.18E+09	5.10E+08
Global warming (GWP100)	kg CO2 eq	1.53E+11	1.89E+11	1.80E+11	1.56E+11	2.42E+11	2.58E+11	1.54E+11
Ozone layer depletion	kg CFC-11 eq	7.65E+03	4.20E+03	8.92E+03	4.12E+03	6.03E+03	1.15E+04	5.76E+03
Human toxicity	kg 1,4-DB eq	5.50E+10	6.94E+10	8.79E+10	5.83E+10	9.03E+10	1.23E+11	5.92E+10
Fresh water aquatic ecotox.	kg 1,4-DB eq	7.42E+10	8.70E+10	1.23E+11	7.47E+10	1.12E+11	1.73E+11	7.49E+10
Marine aquatic ecotoxicity	kg 1,4-DB eq	1.53E+14	1.83E+14	2.53E+14	1.56E+14	2.36E+14	3.57E+14	1.56E+14
Terrestrial ecotoxicity	kg 1,4-DB eq	1.73E+08	2.22E+08	2.75E+08	1.78E+08	3.02E+08	3.84E+08	1.82E+08
Photochemical oxidation	kg C2H4 eq	3.05E+07	4.10E+07	4.55E+07	3.53E+07	5.12E+07	6.49E+07	3.52E+07


100.
90.
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40.
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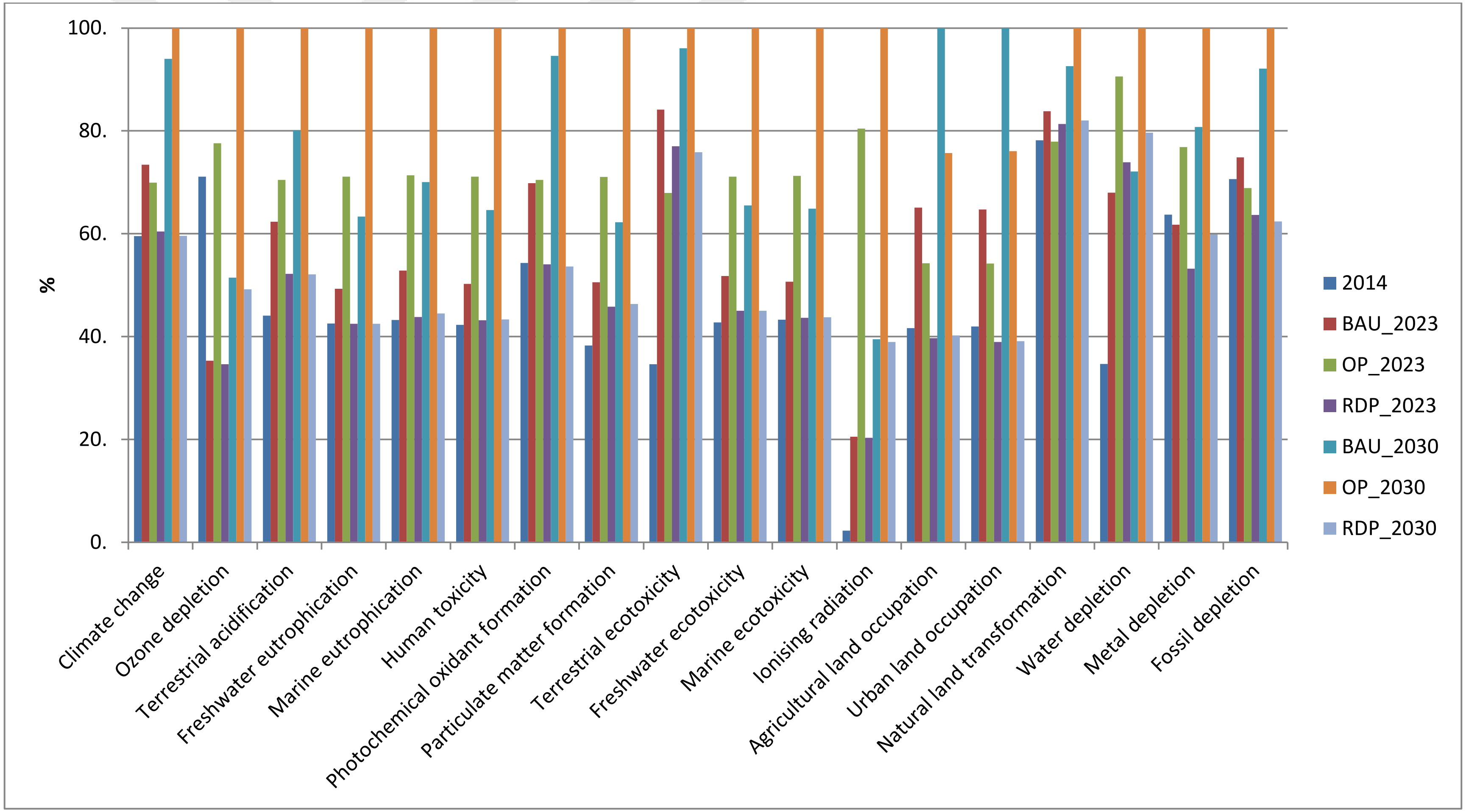
%
Abiotic depletion
Acidification
Eutrophication
Global warming
Ozone layer depletion
Human toxicity
Fresh water aquatic ecotox.
Marine aquatic ecotoxicity
Terrestrial ecotoxicity
Photochemical oxidation
2014
BAU_2023
OP_2023
RDP_2023
BAU_2030
OP_2030
RDP_2030

A12. COMPARISON OF FUTURE SCENARIOS WITH ReCiPe (H) MIDPOINT IMPACT ASSESSMENT METHOD

Impact category	Unit	2014	BAU_2023	OP_2023	RDP_2023	BAU_2030	OP_2030	RDP_2030
Climate change	kg CO_2 eq	1.54E+11	1.90E+11	1.81E+11	1.56E+11	2.43E+11	2.58E+11	1.54E+11
Ozone depletion	kg CFC-11 eq	8.91E+03	4.43E+03	9.73E+03	4.34E+03	6.45E+03	1.25E+04	6.16E+03
Terrestrial acidification	kg SO_2 eq	6.73E+08	9.52E+08	1.08E+09	7.97E+08	1.22E+09	1.53E+09	7.95E+08
Freshwater eutrophication	kg P eq	1.51E+08	1.75E+08	2.53E+08	1.51E+08	2.25E+08	3.55E+08	1.51E+08
Marine eutrophication	kg N eq	4.32E+07	5.28E+07	7.14E+07	4.38E+07	7.01E+07	1.00E+08	4.45E+07
Human toxicity	kg 1,4-DB eq	8.90E+10	1.06E+11	1.50E+11	9.09E+10	1.36E+11	2.10E+11	9.12E+10
Photochemical oxidant formation	kg NMVOC	3.67E+08	4.72E+08	4.76E+08	3.65E+08	6.39E+08	6.76E+08	3.62E+08
Particulate matter formation	kg PM10 eq	1.12E+09	1.47E+09	2.07E+09	1.34E+09	1.82E+09	2.92E+09	1.35E+09
Terrestrial ecotoxicity	kg 1,4-DB eq	1.64E+06	3.99E+06	3.22E+06	3.65E+06	4.55E+06	4.74E+06	3.59E+06
Freshwater ecotoxicity	kg 1,4-DB eq	2.25E+09	2.73E+09	3.74E+09	2.37E+09	3.45E+09	5.26E+09	2.37E+09
Marine ecotoxicity	kg 1,4-DB eq	2.14E+09	2.51E+09	3.53E+09	2.16E+09	3.21E+09	4.95E+09	2.16E+09

Impact category	**Unit**	**2014**	**BAU_2023**	**OP_2023**	**RDP_2023**	**BAU_2030**	**OP_2030**	**RDP_2030**
Ionising radiation	kBq U235 eq	1.63E+09	1.47E+10	5.77E+10	1.46E+10	2.83E+10	7.17E+10	2.79E+10
Agricultural land occupation	m^2a	5.00E+08	7.80E+08	6.51E+08	4.76E+08	1.20E+09	9.07E+08	4.82E+08
Urban land occupation	m^2a	4.36E+08	6.72E+08	5.63E+08	4.05E+08	1.04E+09	7.90E+08	4.07E+08
Natural land transformation	m^2	1.43E+07	1.53E+07	1.42E+07	1.49E+07	1.69E+07	1.83E+07	1.50E+07
Water depletion	m^3	1.00E+09	1.96E+09	2.62E+09	2.13E+09	2.08E+09	2.89E+09	2.30E+09
Metal depletion	kg Fe eq	6.67E+08	6.46E+08	8.04E+08	5.57E+08	8.45E+08	1.05E+09	6.26E+08
Fossil depletion	kg oil eq	4.79E+10	5.08E+10	4.67E+10	4.32E+10	6.24E+10	6.78E+10	4.23E+10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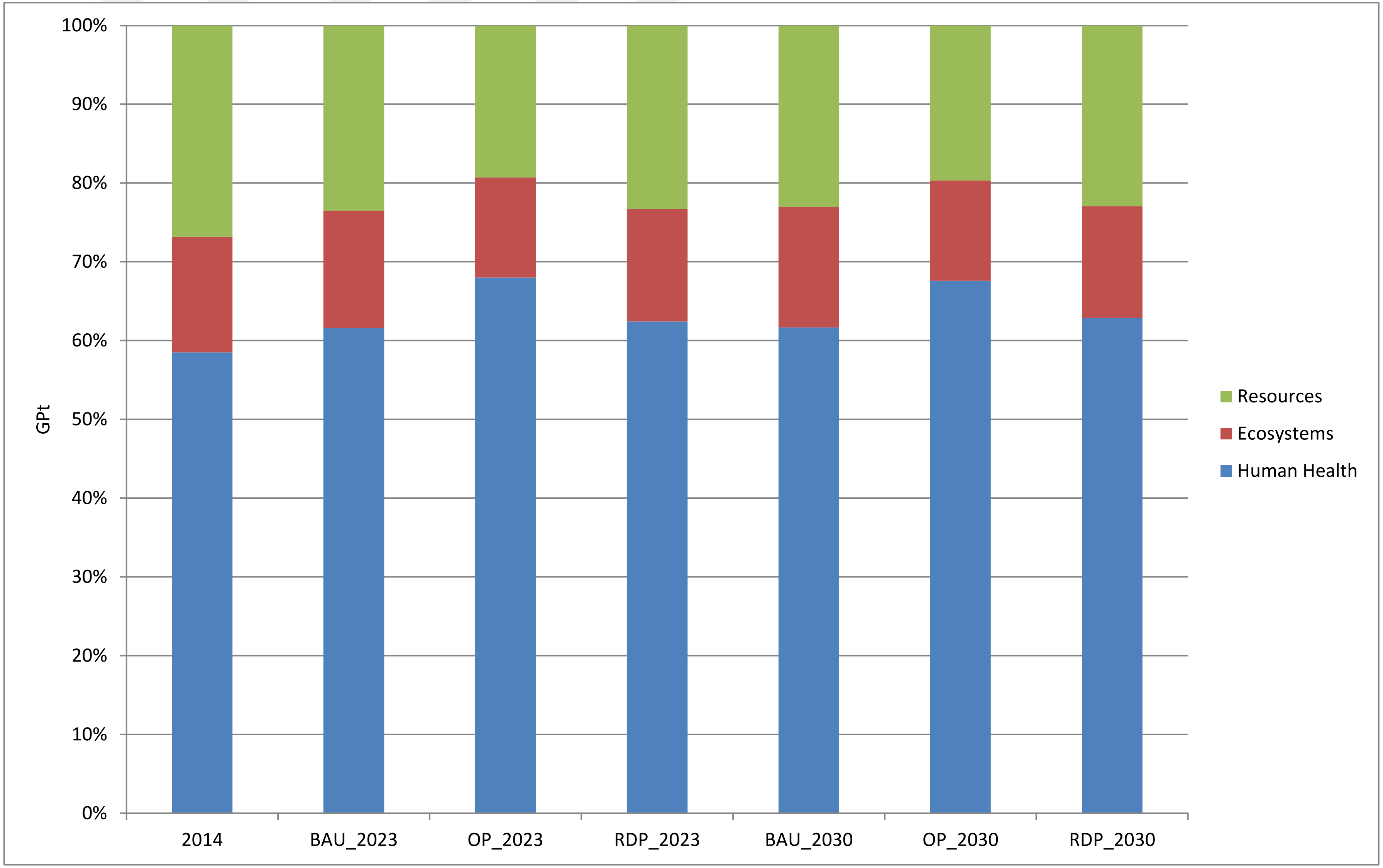
Climate change
Ozone depletion
Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Human toxicity
Photochemical oxidant formation
Particulate matter formation
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Ionising radiation
Agricultural land occupation
Urban land occupation
Natural land transformation
Water depletion
Metal depletion
Fossil depletion
2014
BAU_2023
OP_2023
RDP_2023
BAU_2030
OP_2030
RDP_2030

A13. COMPARISON OF FUTURE SCENARIOS WITH ReCiPe (H) ENDPOINT IMPACT ASSESSMENT METHOD

Damage category	Unit	2014	BAU_2023	OP_2023	RDP_2023	BAU_2030	OP_2030	RDP_2030
Total	GPt	1.92E+01	2.33E+01	2.61E+01	2.00E+01	2.92E+01	3.72E+01	1.99E+01
Human Health	GPt	1.13E+01	1.43E+01	1.78E+01	1.25E+01	1.80E+01	2.51E+01	1.25E+01
Ecosystems	GPt	2.82E+00	3.47E+00	3.32E+00	2.86E+00	4.45E+00	4.73E+00	2.82E+00
Resources	GPt	5.16E+00	5.47E+00	5.04E+00	4.65E+00	6.73E+00	7.31E+00	4.56E+00


100%
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60%
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40%
30%
20%
10%
0%
GPt
2014
BAU_2023
OP_2023
RDP_2023
BAU_2030
OP_2030
RDP_2030
Resources
Ecosystems
Human Health

CV

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Paper Publications:

1. Gokcen A. Ciftcioglu, Fulya Kunter, Gülşah Yılan, and M. A. Neset Kadirgan: “The Importance of Daily Life Phenomena in Chemical Engineering Education”, Engineering Education International Journal of Information and Education Technology, Vol. 7, No. 11, November 2017. DOI: 10.18178/ijiet.2017.7.11.982.
2. Eren Yıldız-Geyhan, Gülşah Yılan, Gökçen Alev Altun-Çiftçioğlu, Mehmet Arif Neşet Kadırgan: “Environmental Analysis of Different Packaging Waste Collection Systems for Istanbul - Turkey Case Study”, Resources, Conservation and Recycling, 2016, 107C, 27-37. DOI:10.1016/j.resconrec.2015.11.013.
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Conference Publications:

1. Gülşah Yılan, Gökçen A. Çiftçioğlu, M. A. Neşet Kadırgan: “Comparison of Electricity Generation Technologies Using Life Cycle Assessment”, 3rd International Conference on Engineering and Natural Sciences (ICENS), 3 – 7 May 2017, Budapest, Hungary (Oral Presentation).

2. Gokcen A. Ciftcioglu, Fulya Kunter, Gülşah Yılan, M. A. Neset Kadirgan: “The Importance of Daily Life Phenomena in Chemical Engineering Education”, 3rd International Conference on Education and Social Sciences (ICESS 2016), 9 – 11 October 2016, Bangkok, Thailand (Oral Presentation)

3. Gülşah Yılan, M. A. Neşet Kadırgan, Gökçen A. Altun-Çiftçioğlu: “Multi-Criteria Decision Analysis (MCDA) of Electricity Generation Options for Sustainable Energy Decision-Making (DM): The Turkey Case”, 10 th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES), 27 September – 2 October 2015, Dubrovnik, Crotia (Oral Presentation)

4. Gülşah Yılan, Burcum Taşkaya, Tuğba Somuncu, Selen Harman, Gökçen A. Altun-Çiftçioğlu, M. A. Neşet Kadırgan: “Parameters to Compare Renewable Energy Sources with Non-Renewable Energy Sources for Power Production”, 3 RD International 100 % Renewable Energy Conference (IRENEC 2013), 27 – 29 June 2013, Maltepe, İstanbul (Oral Presentation)

5. Gülşah Yılan, Osman Özdemir, Kurtul Küçükada: “İdeal Olmayan Piston Akışlı Reaktörlerde Eksensel Dispersiyonun Ürün Dönüşümüne Etkisinin Dağıtılmış Parametreler Modeli Kullanılarak İncelenmesi”, Ulusal Kimya Mühendisliği Kongresi 2012 (UKMK – 10), 3–6 Eylül 2012, Koç Üniversitesi, İstanbul (Oral Presentation)

6. Berna Sarıyar Akbulut, Selim Ceylan, Gülşah Yılan, Dilek Kazan: “Analysis of the Osmolyte Strategy of the Moderately Halophilic Halomonas sp. AAD12”, The 12th International Conference on Systems Biology (ICSB 2011), 28 August – 1 September 2011, Heidelberg, Germany (Poster Presentation).

7. Gülşah Yılan, Uğur Akman, Berna Sarıyar Akbulut: “Understanding of Microbial Adaptation to High Salt Concentrations”, Istanbul Conference on Mathematical Methods and Modelling in Life Sciences and Biomedicine 2009 (ICMMM-LSB), 17 – 21 Ağustos 2009, Yeditepe Üniversitesi, İstanbul (Oral Presentation)

8. Neşet Kadırgan, Gökçen A. Altun Çiftçioğlu, Suat Sevencan, Gülşah Yılan: “Bir İş Merkezinin Güneş Enerjisiyle Soğutulması”, Ulusal Kimya Mühendisliği Kongresi 2008 (UKMK – 8), 26 – 29 August 2008, İnönü Üniversitesi, Malatya (Poster Presentation).