ISTANBUL TECHNICAL UNIVERSITY ★ ENERGY INSTITUTE

AN INVESTIGATION ON RESOURCE LIMITATIONS FOR SUSTAINING A 100% RENEWABLE WORLD

M.Sc. THESIS

Arash EMDADI

Energy Science and Technology Division
Energy Science and Technology Programme

Thesis Advisor: Associate Prof. Dr. Adem TEKİN

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ ENERJİ ENSTİTÜSÜ

%100 YENİLENEBİLİR BİR DÜNYAYI SÜRDÜREBİLMEK İÇİN KAYNAK KISITLAMALARI ÜZERİNE BİR ARAŞTIRMA

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Arash Emdadi, a **M.Sc.** student of ITU **Institute of Energy** student ID **301131034**, successfully defended the **thesis** entitled "**AN INVESTIGATION ON RESOURCE LIMITATIONS FOR SUSTAINING A 100% RENEWABLE WORLD**", which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my heart; my soul; my mother,

FOREWORD

I would like to express my sincere gratitude to my advisors Associate professor Adem Tekin in Istanbul Technical University (ITU) for his helps during this study. Also I would like to thank Doctor Francios Vuille in Ecole Polytechnique Federale de Lausanne (EPFL) for all of his advices, supports and encouragements during this project.

May 2016 Arash Emdadi

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ABBREVIATIONS

GHG	**:** Greenhouse gas
IEA	**:** International Energy Agency
IPCC	**:** Intergovernmental Panel on Climate Change
LCA	**:** Life Cycle Analysis
USGS	**:** United States Geological Survey
WWF	**:** World Wild Fund of Nature

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AN INVESTIGATION ON RESOURCE LIMITATIONS FOR SUSTAINING A 100% RENEWABLE WORLD

SUMMARY

Due to increasing the concentration of greenhouse gases (GHG) which lead to global warming phenomenon, transition from conventional sources of energy (fossil fuels) to clean sources of energy (Renewable energy sources) is necessary. Renewable energy sources are abundont and clean without releasing any pollution to the environment. Today many countries have a strong tendency for developing the renewable energy conversion technologies for decreasing negative effects of fossil fuels. Transition from fossil fuels to renewable energy technologies needs fundamental requirements like resources and materials required in different roadmaps and scenarios of renewable energy technologies. Resources like metals, materials and water are mentioned fundamental requirements that must satisfy our demands in order to 100% renewable energy technologies. In other words, an assessment about available reserves and resources considering their recycling rate, consumption rate and production rate is necessary for reaching to 100% renewable energy plant using long term scenarios. However there are some studies about resources analysis of materials used in renewable energy technologies, mentioned studies do not present a comprehensive study in terms of number of both investigated metals and long term green scenarios. In other words, there is not a clear image about critical metals and materials in different green and long term scenarios for reaching to 100% renewable energy planet. This study investigates the limitations of supply side for 35 metals and materials used in different renewable energy technology considering several long term renewable energy scenarios including IPCC-2050, IPCC-2030, WWF-2050, Hi-REN-IEA2050 and 2DS-IEA2050. This study indicates that there are not sufficient resources and reserves for reaching to a 100% renewable world. In other words there is a huge gap between supply and demand in some key metals required in wind energy conversion technology. Also for metals used in solar energy conversion technologies, resources are not enough to support all the required metals for reaching to 100% renewable world.

% 100 YENİLENEBİLİR BİR DÜNYAYI SÜRDÜREBİLMEK İÇİN KAYNAK KISITLAMALARI ÜZERİNE BİR ARAŞTIRMA

ÖZET

Son yıllarda atmosferdeki karbon dioksit miktarının artmasıyla birlikte yenilenebilir enerji teknolojileri dikkat çekmeye baslamıştır. Yenilenebilir enerji kaynakları, temiz, ucuz ve çok miktarda olduğu için bizim ihtiyaçlarımızı karşılayacak potansiyele sahiptirler. Tüm bu nedenlerden dolayı enerji gereksinimizin fosil yakıtlardan yenilenebilir enerji kaynaklarına donüştürmemiz bir zarurettir ve bu yönde oldukça yoğun araştırmalar yapılmakla birlikte endüstride bu dönüşümün gerekliliğini ve önemini kavramıştır. 2012 yılı verilerine göre, dünyanın kullandığı enerjinin yüzde 11' i yenilenebilir enerji kaynaklarından sağlanmış olup bu miktarın önümüzdeki yıllarda daha da artması beklenmektedir.

Yenilenebilir enerji kaynaklarının günlük enerji tüketimimizde yer alabilmesi için bir dizi teknolojinin geliştirilmesi gerekmektedir. Rüzgar türbinleri, fotovoltaik hücreler, jeotermal, su bitkileri ve okyanus cihazları şu anda geniş kullanım alanı bulmuş yenilenebilir enerji kaynaklarındandır. Yenilenebilir teknolojilere dönüşüm için çeşitli kaynaklara ihtiyaç vardır. Diğer bir deyişle, yenilenebilir enerji teknolojileri inşa edebilmek için farklı hammaddeler kullanmaktyız ve bunların yeterli miktarda bulunması bir zorunluluktur. Bu kaynakların en başında su ve çeşitli metalller yer almaktadır. Alüminyum, sodyum ve mağnezyum gibi metaller yer kabuğunda bol miktarda bulunmalarına rağmen bazı kaynaklar için bu durum geçerli değildir ve hatta bu kaynakları şu anki madencilik teknolojileriyle bol miktarda çıkarmakda mümkün olmayabilir.

Su, farklı uygulamalarda yoğun bir şekilde kullanılan önemli bir kaynaktır. Yeryüzünde çok büyük su kaynakları okyanus formunda bulunmasına rağmen, az miktarda tatlı su kaynakları mevcuttur. Son yıllardaki su kullanımın artmasına paralel olarak yakın zamanda yeryüzünde tatlı su probleminin yaşanması oldukça muhtemeldir. Mevcut teknolojiyle tuzlu ve okyanus sularının tuzdan arındırılması ekonomik değildir ve yüksek maliyetler gerektirmektedir. Bundan dolayı, tatlı su kaynaklarını verimli bir şekilde kullanmak oldukça önemli olmakla birlikte tatlı suyun yenilebilir enerji teknolojilerinde de kullanılıyor olması bu önemi daha da arttırmaktadır. Bu bağlamda, farklı endüstrilerin temiz su kullanma gereksinimleri yenilenebilir enerji teknolojileri için bir sorun teşkil edebilir.

Bazı kaynaklar yer kabuğunda bol miktarda bulunurken, diğer bazı kaynaklar için şu anki madencilik yöntemleri yeterince verimli olmadığı için gelecekteki ihtiyacı karşılamakta sorunlar yaşanabilir. Sülfat ve indiyum bu tabloyu net bir şekilde görmemizi sağlayan örneklerdir. Sülfat kaynakları dünyanın önümüzdeki 100 yıl için ihtiyaçlarını karşılayabilecekken, indiyum kaynakları oldukça kısıtlı olup şu andaki madencilik teknikleriylede yeterince yer kabuğundan elde edilememektedir. Bu çalışmada kritik terimiyle ifade edilen bazı kaynaklar varki, onların üretimi yeterince

yapılamamakla birlikte bu kaynaklar 2030 veya 2050 yıllarındaki yenilenebilir enerji teknolojileri içinde gereken ihtiyacı karşılayamayacak durumdadırlar.

Diğer bir göz önünde bulundurulması gereken konuda geri dönüşüm oranıdır. Kaynakların geri dönüşümü onların daha sonraki zamanlarda kullanılmalarına olanak sağlamaktadır. Eğer geri dönüşüm işlemi olmasaydı, bazı önemli kaynakların gelecekteki ihtiyacı karşılamasında büyük sıkıntılar ortaya çıkabilecekti. Alüminyum, bakır ve çinko gibi bazı kaynakların geri dönüşüm oranları oldukça yüksekken, neodimyum gibi metaller içinse tam tersi bir durum sözkonusudur. Yenilenebilir enerji teknolojilerinin geliştirilmesinde çok farklı kaynaklara ihtiyacmız vardır ve bu kaynakların (metaller ve su) yeterli miktarda bulunması % 100 yenilenebilir bir dünya inşa etmek için gerekli ilk adımdır.

Enerji senaryoları, dünyanın gelecekteki enerji gereksinimini haritalandırmaktadır. Enerji sektöründe her biri farklı parametreler kullanan çok farklı senaryolar mevcuttur. Enerji senaryoları gelecekte kullanılacak olan enerjinin miktarını tahmin etmekte olup, bu çalışmada IPCC, WWF, IEA-HIREN ve IEA-2DS senaryoları 2030 ve 2050 yıllarında ki yenilenebilir enerji kaynaklarının gelişimini incelemekte kullanılmışlardır.

Literatürde yenilenebilir enerji kaynakları üzerine çalışmalar olmasına rağmen, bu çalışmalarda yenilenebilir enerji teknolojilerinde kullanılan tüm metaller değerlendirilmemiş olmakla birlikte, bilinen tüm enerji senaryolarıda göz önüne alınmamıştır. Şu anki çalışmayla hedeflenen, yenilenebilir bir dünya için tüm gerekli kaynakların durumunun irdelenip kritik olanlarımn belirlenmesidir. Bu incelemede ele alınan yenilenebilir enerji teknolojilerinde kullanılan 33 kaynağın miktarı (kg.kWh-1) Ekoinvent veritabanından alınmıştır. Bu veritabanında (SimPro 7 yazılımının içerisinde) yaşam döngüsü analiz bilgileri tüm kaynaklar (yenilenebilir enerji teknolojilerinde kullanılanlarda dahil olmak üzere) için yer almaktadır. Neodimyum ve Disprosiyumun miktarları bu veritabanında yer almamaktadır fakat bu metaller yenilenebilir enerji teknolojilerinde çok önemli bir yere sahip olduklarından dolayı onlara ait miktar bilgileri literatürden alınmıştır. Bu şekilde ilk aşamada incelenen yenilenebilir enerji teknolojilerinde kullanılan toplam kaynak sayısı 35' e çıkmıştır.

Ikinci aşamada, 2030 ve 2050 yılları için yenilenebilir enerji teknolojilerin kullanım miktarları (EJ/yıl) IPCC, WWF, IEA-HIREN ve IEA-2DS senaryoları kullanılarak hesaplanmıştır. Bu çalışmada ele alınan yenilenebilir enerji teknolojileri güneşi (güneş hücreleri (CIS, CdTe ve a-Si), CSP ve güneş termal ısı), rüzgarı (kıyıdan uzak (offshore) ve kıyıya yakın (onshore)), jeotermali (ısı ve güç), biyokütleyi (ısı, elektrik ve yakıt), hidroelektriği ve okyanusu içermektedir. İlk aşamadaki hesaplamalar metallerin yeryüzündeki mevcut kaynak ve rezervleri göz önüne alınarak yapılmıştır. Bu hesaplamalardan 16 metalin kritik olduğu sonucu bulunmuştur. Bu metaller, Zn, Co, In, Nd, Cu, Mo, Au, Re, Cr, Cd, Ni, Zr, Pt, Te, Dy ve Te' dir.

Çalışmanın üçüncü aşamasında ikinci adımda elde edilen sonuçlar daha detaylı incelenmiştir. Birikim miktarları özellikle kritik olan 16 metal için hesaplanmıştır. Bu birikim hesaplamalarında tüketim hızı, üretim hızı ve geri dönüşüm oranı kullanılmıştır. Üretim ve tüketim hızları sabit kabul edilirken en son bulunmuş geri dönüşüm oranı hesaplamalarda kullanılmıştır. Dördüncü aşamada da kritik olarak belirlenen 16 metalin birikim miktarları, bu metallerin rezervleri, kaynakları 2030 ve

2050 yıllarında ihtiyaç duyulan miktarlarla karşılaştırıldı. Son aşama, 6 metalin kritik olduğunu ve diğer 10 tanesinin ise geri dönüşüm ile 2030 ve 2050 yılları için yenilenebilir enerji teknolojilerde ki gereksinimi karşılayabileceğini ortaya koymuştur. Kritik olduğu belirlenen altı metal Co, Nd, Dy, In, T eve Cd' dir.

Kadmiyum güneş hücrelerinde (CdTe) kullanılmakta olup bu teknolojinin gelimesinde büyük rol oynamıştır. Güneş hücreleri IPCC-2050 senaryosunda büyük bir paya sahiptirler ve bu yüzden de bu metal 2050 için kritik durumda olabilir. Tez kapsamında yapılan hesaplamalar bu metalin tüm senaryalarda kritik konumda olduğunu göstermektedir. Diğer bir kritik metal kobalttır. Hesaplamalar bu metale IPCC-2050 senaryasunda ihtiyacın 59.4 milyon ton olduğunu göstermektedir ki bu rakam şu anda ki kobalt rezervinin 8 katıdır. Kobalt kaynakları yer kabuğunda oldukça fazladır fakat madencilik teknikleriyle bol miktarda bu metal üretilemememektedir ve bundan dolayıda üretim ile tüketim arasında büyük bir boşluk söz konusudur. İndiyum güneş hücrelerinde (CIS) kullanılan diğer önemli bir metaldir. Bu metalin geri dönüşüm oranı (% 1) oldukça azdır ve bu yüzden de bu metal kritik konumdadır. Kaynaklar ve rezervlerde indiyum için yeterli değildir. Neodimyum ve disprotiyum rüzgar türbini teknolojilerinde kullanılan iki önemli metaldir. Bu metaller endüstride yoğun kullanıldıklarından dolayı büyük miktarlarda ihtiyaç duyulmaktadır. Başka bir ifadeyle, yeni rüzgar türbinlerin yapılması bu iki metale bağlıdır. Kaynak noktasında bu iki metal için bir sorun olmamasına rağmen şu anki madencilik teknikleriyle yüksek miktarda üretimleri yapılamamaktadır. Tellür, CdTe güneş hücrelerinde kullanılan diğer bir kritik metaldir. 2050 yılında kullanılması beklenen tellür miktarı bu metalin kaynaklarının %12' sine tekabül etmektedir. Bu metalin geri dönüşüm oranıda (%1) oldukça düşüktür.

Tez kapsamında ele alınan farklı senaryolar değerlendirildiğinde, suyun, sürdürülebilir bir yenilebilir enerjinin hüküm sürdüğü dünya için yeterince bulunduğu anlaşılmaktadır.

Bu çalışmada elde edilen sonuçlara göre %100 yenilenebilir enerji kullanan dünya şu anki üretim ve geri dönüşüm teknolojileriyle mümkün görünmemektedir. Bulunan kritik metaller, rüzgar ve güneş gibi önemli yenilenebilir enerji teknolojilerinin geliştirilmesinde temel rol almaktadırlar ve bu metaller 2030 ve 2050' de yenilenebilir enerjinin hüküm sürdüğü bir dünyanın ihtiyaçlarını karşılayamamaktadırlar.

1. INTRODUCTION

Need for a sustainable and reliable supply of energy to cover our daily demand is undeniable to sustain economic growth and maintain prosperity and comfort[1]. Due to the ongoing increase in energy consumption of finite

fossil resources and resulting increase in concentration of carbon dioxide in the Earth atmosphere, renewable energy resources are attracted increasing attention globally as alternative energy resources. To decrease the footprint of carbon dioxide and also to decrease the consumption of fossil fuels, renewable energy resources including: solar power [2], geothermal power [3], wind power [4], small hydropower [5], energy from biomass [6], tidal power [7] and wave power [8] can be converted to the electricity and heat by different conversion technologies. The global energy consumption and share of renewable energy resources in 2012 are presented in Figure 1.1.

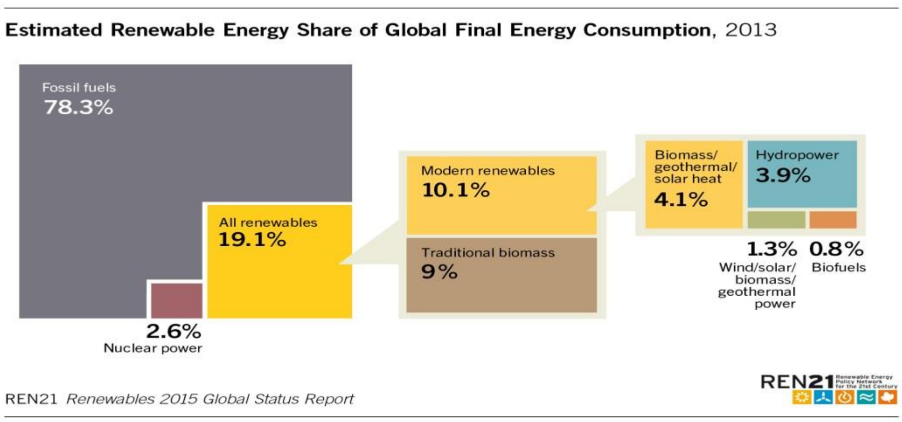


Figure 1.1 : Global primary energy consumption by fuel type in 2012 [9].

As it is shown in Fig. 1.1, modern renewable energy resources form about 10 % of world's primary energy consumption in 2012. There are many energy scenarios that predict the roadmap of renewable energy deployment in near term and long term periods. Each scenario considers different parameters to predict future energy demands. Scenarios like International Energy Agency (IEA), Intergovernmental Panel on Climate Change (IPCC) and World Wide Fund for Nature (WWF) can be considered as a scenario that has determined the renewable energy deployment in 2030 and 2050. Based on some long mentioned scenarios share of renewable energy in global primary energy consumption will increase in next decades so that some scenarios predict a value between 50-100% for mentioned value in their long-term roadmaps.

For producing the energy from renewable energy resources, some primary resources such as different metals, elements and water play an important role. In the crust of earth there are many resources which are used in renewable energy conversion technologies such as: Copper, Aluminum and Nickel. While some of the materials are abundant, some others are rare and hard to extract by current level of mining and extracting technologies. For some materials, mining and extraction technologies can provide sufficient amount for our demands in the energy or others sectors while, some others like Rare Earth Metals (REMs) need new and more efficient extraction and separation technologies to meet our current and future demands.

Also water can be considered as considerable resource which is mainly used in many processes for producing materials and devices that are used in renewable energy conversion technologies. Studies show that while there is a huge amount of water in the hydrosphere of earth, only a small amount can be considered as fresh water. Global geographical distribution of fresh water is the main constraint for freshwater availability so that in some regions of earth there is plenty amount of fresh water while some other regions lack fresh water. In other words, water is a vital resource and a comprehensive management must be applied for water utilization in energy sector. Global water distribution is presented in Figure 1.2 [10].

Except demand for resources in renewable energy technologies, others industries also consume metals and materials which are used in renewable energy conversion technologies. For example in 2011 about 28 and 14 % of global Copper production were used in "Building & Construction" and "Machinery & Equipment" sectors respectively. In the same year about 65 % of global production of Nickel is used in stainless steel industries. All of this means that there is a close competition on primary materials usage between renewable energy conversion technologies and other consumer sectors such as: transport, construction and etc.

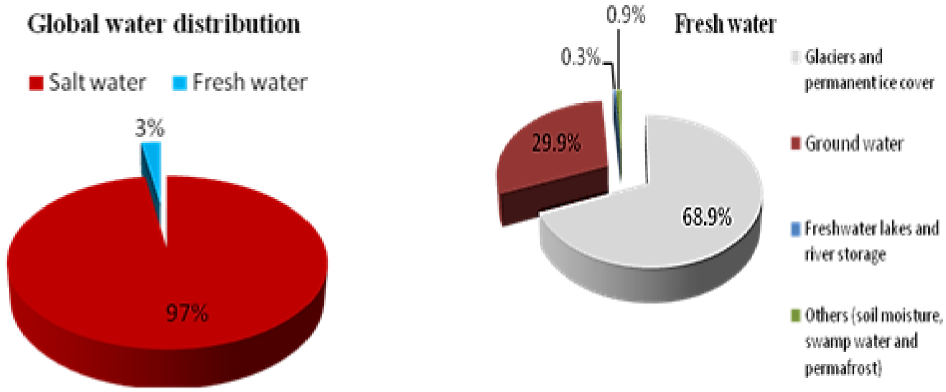


Figure 1.2 : Global distribution of water and different fractions of fresh water in the earth. [10]

Availability of metals in resources and reserves for satisfying consumer technologies in long term is another challenge so that it is essential to detect the critical resources used in renewable energy industries. For some materials there are not huge resources in the crust of earth while for some others, the mining and extraction methods are not efficient to provide our future demand. For example Sodium sulfate is sufficient to last hundreds of years with present consuming rate while for some other materials like Indium and tellurium, there are limited resources and low production rate. The term critical can be considered for metals that their supply won't satisfy their demand in 2050 for renewable energy technologies. In other words, availability of metals in their recognized resources and reserves for providing our demands in renewable energy technologies based on the investigated scenarios determines the criticality of metals and materials.

Another important parameter affecting on evaluation of resources capacity is recycling rate of materials and metals. Recycling of strategic elements for achieving to a maximum production is essential so that without recycling process, the resources would not be sustainable. For example in 2014, about 52% of produced Zinc from refining process was recovered in Unıted States. Mentioned value is about 95000 tons which is about 10 % of zinc production of United States in 2014 [11]. For some materials like Rare Earth Metals (REMs) limited quantities can be recycled. This issue is a challenge for these metals due to their low production rate in the world [11]. Aluminum, Magnesium, Lead, Zinc, Copper, Nickel and Cobalt can be considered as metals and elements that can be recycled and recovered by using different techniques.

Reaching to a world consuming renewable energy sources needs different metal and materials and lack of resources for renewable energy technologies is the first obstacle for this purpose. In other words, determining the situation of resources and their potential for providing demands of renewable energy technologies in 2050 using long term roadmaps is the first step of investigation on reaching to a 100% renewable energy world.

Altough there are some studies that have investigated availability of some metals and materials used in renewable energy technologies using some roadmaps, still a comprehensive study about all the main metals and materials used in renewable energy technologies in different key scenarios is not available. This study tries to investigate resources limitations of reaching to a 100% renewable energy world using long term renewable energy road maps. In this study a comprehensive number of resources used in renewable energy technologies are investigated and their availability using scenarios like IPCC-2050, IPCC-2030, WWF-2050, HiREN-2050 and 2DS-2050 are analyzed.

1.1 Purpose of Thesis

This study investigates resources limitations for achieving a 100 % renewable world in 2030 and 2050 using renewable energy sources. In other words, through long term scenarios like IPCC and WWF as our long-term roadmaps, the thesis analyzes the availability of resources used in renewable energy conversion technologies.

In this study, of 35 resources including water and different metals for renewable energy technologies including solar energy, wind energy, energy from biomass, hydropower and geothermal energy consisting break down technologies using long term scenarios are investigated. The availability of mentioned resources is investigated based on long term and renewable world scenarios including IPCC-2050, IPCC-2030, WWF-2050, HiRen-2050 and 2DS-2050. Recycling rates of metals are also investigated in this research. Amount of materials that can be recycled to the consumption cycle of resources are calculated to determine the exact value of material and resources availability in 2030 and 2050. To obtain an exact assessment about criticality of metals and materials, through employing recycling rate, production rate and recycling rat the accumulation of materials and metals are calculated. Obtained results are compared with available resources and reserves so that an exact assessment about criticality of metals utilized in renewable energy technologies was evaluated. This study investigates and detects the limitations in terms of availability and criticality of metals, materials and water for reaching to a renewable energy world in 2030 or 2050 based on renewable energy deployment scenarios. Main objectives of this thesis can be considered as i) determining the materials and metals required in renewable energy conversion technologies based on long term (2030 and 2050) renewable energy scenarios ii) calculating the accumulation of metals and materials based on current recycling rate, consumption rate and production rate iii) detecting critical metals and materials through comparing results of calculations with available resources and reserves.

1.2 Scope of Analysis

This study investigates the supply side of renewable energy conversion technologies for reaching to a 100% renewable energy in the world based on long term renewable energy scenarios. Mentioned deployment scenarios predict the potential of renewable energy technology in a global scale until 2030 and 2050. Scope of this study is defined in the following items,

Scale: This study investigates the required materials in a global scale.

Time horizon: Time horizon considered in this study is based on 2030 and 2050 scenarios investigated.

Scenario: Energy scenarios and roadmaps considered in this study are: the IPCC, WWF, the IEA-HiREN and IEA-2DS-hire.

Supply side: This study investigates the supply side of renewable energy technologies in 2030 and 2050 regardless of the demand side and policy.

Technology: This study investigates required metals in different renewable energy sources including: Solar energy (Concentrated Solar Power (CSP), solar thermal energy, thin film Photovoltaics (PVs)), wind energy (offshore and onshore), geothermal energy (geothermal heat and electricity), bioenergy (bio-heat and power, bio-fuel) and hydro (ocean energy and hydropower).

Metals and materials: In this study, 35 Resources including water and different metals used in renewable energy technologies are investigated. Mentioned metals and materials are extracted from Life Cyclr Assessment (LCA) database of renewable energy technologies. Investigated Resources are: Aluminum (Al), Bromine (Br), Cadmium (Cd), Chromium (Cr), Cobalt (Co), Copper (Cu), Fluorspar (CaF_2), Gallium (Ga), Gold (Au), Indium (In) , Lead (Pb), lithium (Li), Magnesite ($MgCO_3$), Magnesium (Mg), Manganese (Mn), Molybdenum (Mo), neodymium (Nd), Nickel (Ni), Palladium (Pd), Phosphorus (P), Platinum (Pt), Potassium K, Rhenium (Re), rhodium (Rh), silver (Ag), sodium (Na), Dysprosium (Dy), Sulfur (S), Tantalum (Ta), Tellurium (Te), Tin (Sn) , Titanium (Ti), Zinc (Zn), Zirconium (Zr) and water.

1.3 Literature Review

Need for a sustainable and reliable supply of energy to cover our daily demand is undeniable to sustain economic growth and maintain prosperity and comfort [1]. Due to the ongoing increase in energy consumption of finite fossil resources and resulting increase in concentration of carbon dioxide in the atmosphere of earth, renewable energy resources have attracted increasing attention globally as alternative energy resources. To decrease the footprint of carbon dioxide and also to decrease the consumption of fossil fuels, renewable energy sources are essential as a replacement of fossil fuels and related technologies. For producing the energy from renewable energy resources, some primary resources such as different metals, elements and water play an important role. Availability of resources (water, metals and materials) for satisfying the demands of renewable energy technologies in long term is a challenge so that it is essential to detect the critical resources used in renewable energy industries. Another important parameter affecting the evaluation of resources capacity is recycling rate of materials and metals. Recycling of strategic elements for achieving to a maximum production is essential so that without recycling process, the resources would not be sustainable.

There are studies in the literature about desirable aspects of criticality determination, availability of resources for sustainable development considering their usage in different applications and also different factors affecting on the criticalitiy factor of metals [12-17]. Transition from fossil fuels to low-carbon power generation and its impact on metals and materials is investigated [18]. In this study, using LCA database the authors investigated the intensity of metals consumption in low carbon technologies in compared with current technologies of energy production [18]. Based on results of this study, transition to low-carbon power generation will consume more metals and materials compared to the current technologies while it decreases the amount of released pullutants to the atmosphere [18]. Bradshaw and Hamacher [19] investigated the scarcity of metals used in sustainable systems of energy supply and presented the definition of scarsity for metals and materials used in mentioned systems describing scarcity by criterias including: steady decrease in global average grade of ores extracted during the time and increase in price of extracted metals which it is hard to be compansated by improving and upgrading mining and extraction technologies. Vesborg and Jaramillo [20] have investigated the supply of chemical elements for one TerraWatt hour (TWh) energy production through each renewable energy technology. Based on thids study, for producing one TW_{avg} of electricity through solar energy conversion technologies, 350 kt absorber materials and metals and also 3.5 Million ton of tin is required. Results of this study indicate that for wind energ conversion technologies (wind turbines) 750 kt of neodymium and 50 kt of dysprotium is required for producing 1 TW electricity using wind turbine with high speed generators while for low speed /gearless wind turbines higher amount of dyprosium is needed [20]. Results of another study [21] on availability of Dy considering both supply and demand sides in long and short terms indicates that growth of demand for dysprosium can effect wind energy conversion technologies (wind turbines) because of fast growing of consumer industries like electric vehicles and limited production capacity. The impact of Cu scarcity on the efficiency of global renewable energy scenarios in longterm (2050) is investigated by Harmsen et al. [22]. Based on this study, however there are huge reserves and resources of copper, increasing the demand for renewable energy technologies will lead to increase in copper production which results in increase in energy consumption for production. Platinum is another metal which is used in many renewable energy technologies. Availability of platinum resources is studied by Elshkaki [23] through developing a dynamic model of intentional and non-intentional flows and stocks of platinum and considering fuel cells deployment in long term. In this study supply and demand of platinum considering secondary resources of platinum were also investigated. Results of this model indicate that resources of platinum will be depleted before the end of century with or without considering fuel cell vehicles indicating a possible constraint for platinum. Availability of some resources like cobalt are investigated in the literature reporting total resources of cobalt including recoverable resources are 42.7 million tons which is sufficient for several decades [24]. There are some other studies about lead indicating no limitation and constraint for this metals in for long term demands [6]. Results of studies [25-32] related to material availability of thin film solar cells indicate the potential of facing with resources constraint about some technologies like CdTe or CIGS thin film solar cells due to some parameters like price of metals, availability of them in longterm and also their dependence on production of their parent metals like copper, zinc, tin and aluminum. Kavlak et al. [16] investigated metal requirement for fast development of photovoltaics (PVs) considering future energy scenarios and hystorical growth rate of different metals used in PVs including: indium, gallium, selenium, tellurium, cadmium and silicon. Results of their study indicate that scalability of In, Te and Se will fall in 2030 due to limited reserves of mentioned metals. Results of this study also indicate that in case of Ga and Cd there is not a bottleneck of scalability because of sufficient reserves of Ga and also decrease in consumption of Cd in non-PV sectors which is related to toxicity of this metal [16]. In the case of crystalline- Si solar cells, achieving to a TW scale energy will lead to depletion in silver resources. Another disdvantage of crystalline solar cells is their high demand of energy in fabrication process [33]. High conductivity of silver makes it as an ideal metal used in silicon photovoltaic technology and also a favourable metal in coating of mirrors used in concentrated solar power technologies. Grandell and Thorenz [34] have investigated supply risk of silver in solar energy conversion technologies considering different scenarios. Results of mentioned study indicate the bottleneck in availability of silver for satisfying demands in different solar energy conversion technologies like concentrated solar power technologies, crystalline-Si and thin film solar cells. To overcome mentioned limitations, some solutions including developing and improving recycling technologies, employing alternative materials instead of scarce materials, applying new fabrication process with low energy consumption and reducing the thickness of semiconductor layers are suggested [29, 33, 35] however considering alternative metals (for example replacing silver by aluminum) instead of critical metals will decrease the efficiency of system and finally produced electricity will be decreased [34].

Elshkaki and Graedel [36] have investigated the availability of metals for renewable energy technologies using some policy and market scenarios. Based on results of mentioned study, wind energy technologies will not face with any problem in terms of resources while in solar energy conversion technologies, Te has the potential to be critical in terms of production capacity and resources. Availability of some metals like copper, aluminum and some materials like glass and cement used in renewable energy technologies considering a long term scenario like WWF are investigated by Vidal et al. [37]. Results of this study indicate that there are enough resources of copper and aluminum for renewable energy technologies so that we will not face with lack of these metals in 2030 or 2050. Some metals like silver, indium, tellurium are used in different solar PV energy conversion technologies. Silver is a fundamental metal used in silicone (c-Si) solar cells as conducting materials in the electrodes. Based on predicted growth of a-Si cells in IEA BLUE Map Hi-REN scenario, consumption of silver in PV industries will grow to 3300-9300 tonnes by 2050 indicating a constraint in terms of resources availability [38]. For thin film PVs, metals including indium and tellurium can be considered as critical resources. In case of Indium, there is a close competition between other consumer industries and thin film solar cells (CIGS/CIS) production. Main fraction of supplied indium is used in producing Liquid Crystal Displays (LCD) so that this sector consumes more than 50% of produced indium. Based on the technology mix scenario CIGS/CIS market will consume 20% of supplied indium in 2025 which is about 766 tons/year. This value is 130 tons more that the total primary supply of indium in 2011 [38]. Availability of neodymium and some other metals including cadmium, gallium, indium, tellurium and selenium in 2050 considering 60% renewable and 40% non renewable energy systems in the world are investigated by Bradshaw et al [39]. Share of renewable energy systems in this study for solar PVs, wind and solar thermal is equal and also the share of both biomass energy (for heating purpose) and hydropower are considered 10 %. In this study the global energy demand in 2011 was considered 147900 TWh using the value which is determined by International Energy Agency (IEA) [9] and according to the assumption of authors in this study, the global consumption of energy in 2050 will double the value determined by IEA for 2011. Based on this study about 3 million tons of neodymium is required for both wind turbines and also for transportation sector which is not a huge fraction of global reserves of neodymium. In CdTe solar cells, the required value for Cd and Te based on this study will be between 0.5 and 0.6 million tons in 2050 respectively indicating a critical status (lack of resources) for Te and also in the case of Cd the potential of facing with constraint [39]. For CIGS solar cells required values in 2050 will be 0.1, 0.05 and 0.3 million tons for indium, gallium and selenium respectively which are higher than their reserves based on USGS data [11].

However it has been investigated availability of some metals and materials used in renewable energy technologies using some roadmaps, still a comprehensive study about all the metals and materials used in renewable energy technologies in different key scenarios is not available. This study tries to investigate resources limitations for reaching to a renewable energy world using long term renewable energy road maps. In this study a comprehensive number of resources used in renewable energy technologies and their availability using scenarios like IPCC, WWF, IEA-HiREN and IEA-2DS are analyzed. These scenarios are main scenarios considering renewable energy technologies in their roadmaps so that WWF considers a 100% renewable energy world in 2050 while for other scenarios like scenarios presented by IEA this value is around 50% [9].

1.4 Method

To evaluate the criticality of metals and materials used in renewable energy technologies, it is necessary to detect main metals and materials used in renewable energy technologies. Except detecting mentioned metals and materials, knowledge about fractional mass ($kg.kWh^{-1}$) of each metal used in the renewable energy technologies is essential. Full life cycle analysis can be considered as a technique for assessing the environmental impacts associated with all the stages of a product's life from cradle to grave (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling). In other words, using LCA database gives required data about consumed metals and materials in renewable energy technologies. In this study, 34 metals and water are investigated. Using SimaPro7 software, LCA data of consumed metals ($kg.kWh^{-1}$)

and water ($m^3.kWh^{-1}$) were obtained. Information related to three resources including Nd and Dy were obtained through available data in the literature. All in all, 35 resources were studied in this study. Considering investigated roadmaps in this study (IPPC 2050, IPCC 2030, WWF), shares of different renewable energy technologies in global energy demand in 2030 or 2050 are obtained. In the next step required metals and water for different renewable energy technologies were calculated and also were compared with available resourses and available current reserves in the earth. Depending on amount of available resources and reserves for metals, their condition is categorized. To earn an exact assessment about accumulation of metals, in the next step recycling rate of metals were applied in the calculations. Using a formula and a model designed for life cycle of metals, the accumulation of metals are calculated and an exact evaluation about condition of metals and materials considering annual consumption and production, consumption, production and recycling rate obtained as are presented in following sections. Renewable energy sources and related break down technologies investigated in this study are: wind energy (on shore and off shore turbines), solar energy (PVs including CdTe, CIS and amorphous silicon solar cells, CSP and Solar thermal energy), Biomass (heat, bio-fuel and electricity), ocean energy and hydropower. Share of different solar PVs were considered equal (0.33) in this study. Also in calculations of biofuel, 50 % of biofuel was assumed to be biodiesel and remaining 50 % was selected as bio-methanol (95% ethanol). This study was performed in four steps;

Mass balance: a mass balance in global scale between predicted energy demands in 2030 and 2050 and our resources including metals, materials and water.

First screening step: selecting materials with potential of facing with shortage in 2050 and 2030. Using a comparison between available reserves, resources and demand in 2030 or 2050 some potential metals were screened.

Second screening step: selected metals in second step were analyzed using different parameters like consumption rate, production rate, recycling rate and accumulation.

Final selection: After step 3, final metals were selected through comparing accumulation, resources and reserves of metals.

Based on definitions presented by Unites States Geological Survey (USGS) the resources is referred to the "concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible" and reserves is referred to "that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth". In this study all the data related to reserves and resources of metals and materials are obtained from USGS database [40-67]. Values related to recycling rate of metals are presented in Table 1 are results of study by Graedel et al. [68]. Using parameters like consumption (C), Production (P), recycling rate (r), production rate (x) and consumption rate (y), the accumulation of each metal and material is calculated. In this study it is assumed that in each year the accumulation (A) can be considered as sum of difference between production and consumption (P-C) plus recycling rate multiplied by consumption of metal or material (rC). Based on this model for each model;

In the first year;

$$A_1 = (P - C) + rC \tag{1.1}$$

At the second year considering production rate (x) and consumption rate (y);

$$\begin{aligned} A_2 &= (P + Px) - (C + Cy) + (C + Cy)r + A_1 = \\ &(P + Px) - (C + Cy) + (C + Cy)r + (P - C) + rC \end{aligned} \tag{1.2}$$

In this model, consumption and production rates are constant. To have an acceptable evaluation about the rate that metals consume or produce, historical data related to production and consumption value of metals were used so that at the next step rates of consumption and production obtained using curve fitting. In this model, due to constant rate of consumption and production, global production and consumption of each metal will increase or decrease in compared with previous year. Thus to calculate total consumption and total production between first year and nth year, it is possible to consider an Arithmetic progression. Assuming   and   as production and consumption in year (i), it is possible to write;

$$P_n = P_1 + (n-1)d \tag{1.3}$$

$$P_{total} = P_1 + (P_1 + d) + (P_1 + 2d) + ... + (P_1 + (n-1)d) \tag{1.4}$$

$$P_{total} = (P_n - (n-1)d) + (P_n - (n-2)d) + ... + (P_n - d) + P_n \tag{1.5}$$

$$2P_{total} = n(P_1 + P_n) \tag{1.6}$$

$$P_{total} = P_1 + P_2 + ... + P_n = \frac{n}{2}(P_1 + P_n) \tag{1.7}$$

$$C_{total} = C_1 + C_2 + ... + C_n = \frac{n}{2}(C_1 + C_n) \tag{1.8}$$

Therefore;

$$A_{total} = P_{total} - C_{total} + rC_{total} = \frac{n}{2}(P_1 + P_n) - \frac{n}{2}(C_1 + C_n) + r\frac{n}{2}(C_1 + C_n)$$
$$= \frac{n}{2}((P_1 - C_1 + rC_1) + (P_n - C_n + rC_n)) \tag{1.9}$$

In this study the availability of metals and materials are investigated based on resources and reserves. Some metals like REMs have huge resources while limited reserves are available for some metals like Aluminum. Using hystorical data of USGS, consumption and production rate of metals were obtained. These rates were used for accumulation calculation of some metals that were detected to be critical after first screening step. For example global consumption and production of chromium in recent years are presented in Figure 1.3.

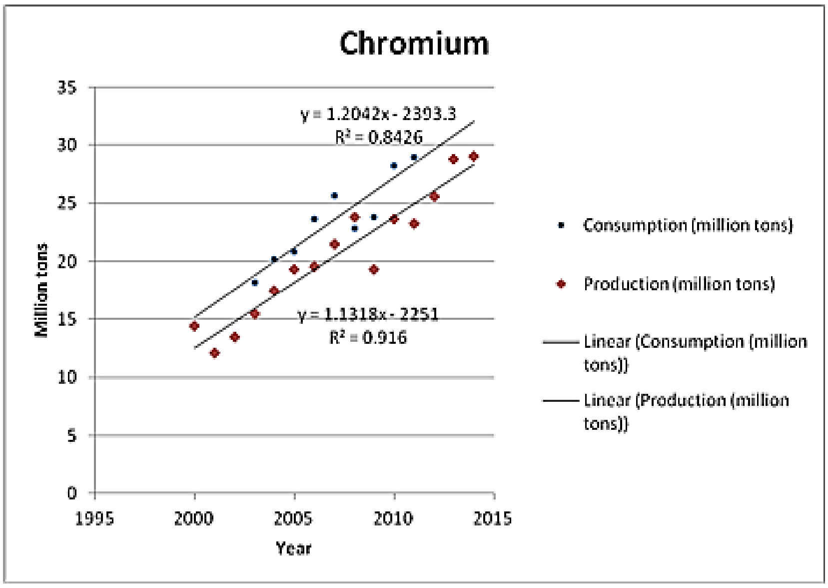


Figure 1.3 : World consumption and production of Chromium between 2000-2015

Table 1.1 : Employed recycling rate for calculating accumulation of some metals in this study.

Metal Name	Recycling Rate (%)
Cr	50
Co	50
Au	50
Mn	50
Ni	50
Re	50
Ag	50
Ti	50
Zn	50
Pt	50
Mo	30
Cd	20
Ga	1
In	1
Nd	1
Ta	1
Te	1
Zr	1

2. TOWARD A 100% RENEWABLE ENERGY WORLD

2.1 Renewable Energy Sources and Conversion Technologies

Solar energy, wind energy, biomass energy, hydroelectric and geothermal energy are the main renewable energy sources including different conversion technologies which will be investigated in the following sections.

2.1.1 Solar energy

As the origin of our planet, sunlight is the source of other renewable energy sources like wind, hydropower and biomass. The origin of solar radiations transmitted by the surface of sun is turning sun's mass per second into energy. Mentioned mass of sun is formed mostly from helium and hydrogen. Two components of solar energy when they reach to surface of earth are direct radiation and diffusion radiation. The energy which is received by the earth is about 885 million terawatt hours (TWh) annually which can be considered equal to 6200 times of human's commercial primary energy consumption in 2008 and also equal with 4200 times of the energy consumption in 2035 based on roadmap of International Energy Agency (IEA) [9]. By capturing all the annual solar energy sent by sun, this amount will be sufficient for human's energy consumption more than 6000 years while other fossil energy resources including oil, natural gas and coil will be able to support our demands for 46, 58 and 150 years respectively with present usage rate.

Technologies for converting the energy received by sun are discussed in the following sections. Based on the report by IPCC in 2011[69], global technical potential of renewable energy sources are investigated using previous studies. Based on the results of this report, even lower level evaluated for producing energy by direct solar energy is higher than the current global primary energy supply. The upper and lower ranges suggested for technical potential of direct solar energy are about 2000 and 60000 EJ per year respectively. Lower bound suggested for solar energy is more than of upper bound of any other renewable energy source like biomass, geothermal energy, wind energy, hydropower and ocean energy. Solar energy can be converted to electricity and heat by different conversion technologies. Conversion technologies of solar energy are discussed in the following sections.

2.1.1.1 Solar heat

The devices which are used for converting solar energy to heat normally have receptive surface to the sunlight including direct radiation and diffusion radiation. The surface absorbs incoming sunlight and turns it into heat. There are different devices for converting the sunlight to heat including flat plate collectors, evacuated tube collectors, CPC collectors, ovens, Fresnel reflectors, parabolic dishes, scheffler dishes and solar towers. Mentioned devices can be utilized in different technologies of heat production including solar water heaters [70-72], solar cookers [73-75], solar driers[76-79], solar ponds [80-82], solar architecture [83-85], solar air conditioning [86-88], solar chimneys [89-91] solar power plants [92, 93] and solar stills-water purification and distillation [94-96].

2.1.1.2 Solar thermal electricity

In this technology the sunlight is concentrated on a fluid in order to increase the temperature of working fluid. Through a heat machine, some of the stored heat in the fluid is converted to the electricity [97]. Following technologies are applied in order to convert solar thermal energy to the electricity:

Parabolic troughs and linear fresnel reflectors

This technology is based on heat transfer to a fluid known as heat transfer fluid and then preheating the water in the heat exchanger to superheat it [98, 99]. Mentioned heat transfer fluid is usually some synthetic oils. Superheated steam as working fluid derives a turbine which is connected with a generator for electricity generation. As a part of thermodynamic cycle, condensed and cooled water is recycled in the heat exchanger and then reheated by the hot oil.

Solar towers and dishes

In compared with trough planes, solar towers are younger. This technology has advantages in terms of efficiency and cost in compared with other solar thermal energy technologies. In other words, due to higher operating temperature and lower cost of solar collectors, it is possible to produce power cheaper in compared with current parabolic trough designs. There are some solar towers in commercial scales in Spain and the United States. Due to the high latent heat of some salts, they are used as high temperature fluid and storage medium in these plants. Molten nitrate salt mixture formed by salts of sodium nitrate (60%) and potassium nitrate (40%) can be used as high temperature fluid in mentioned plants [100, 101]. These salts can store the heat in their structure due to high heat capacity so that the plant can operate at night where there is no trace of sunlight. By concentrating the sunlight to top of the tower the temperature of salt increases to 565 ºC and 550 ºC respectively which is enough to turn the water into superheat state and therefore derive the turbine. Figure 1.4 shows the process of electricity generation by molten-salt solar tower.

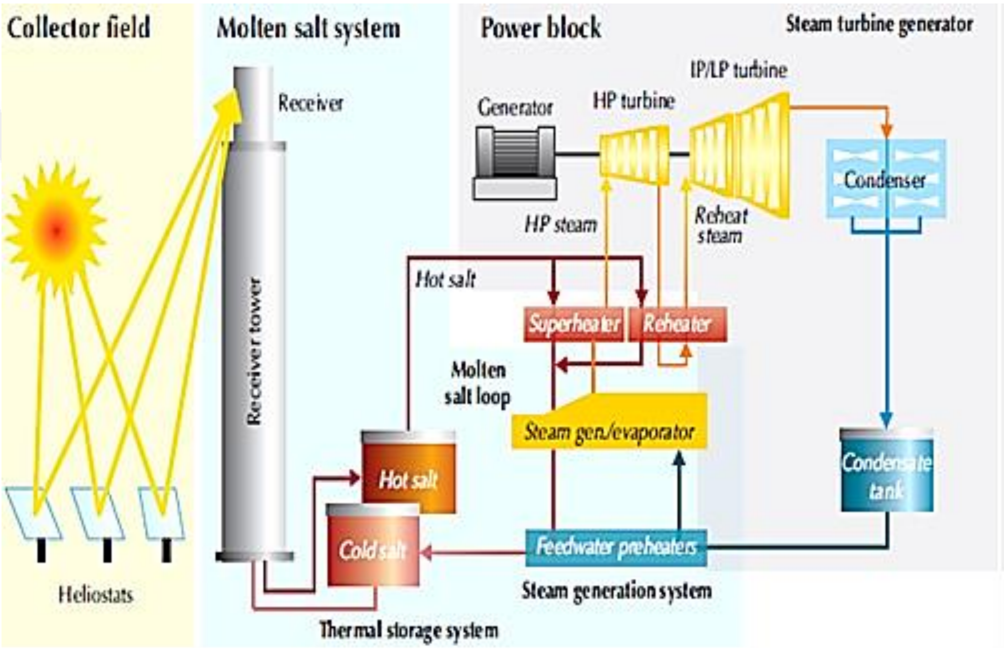


Figure 1.4 : Solar tower for electricity generation. [102]

2.1.1.3 Solar photovoltaics

Solar Photovoltaics (PVs) are used for direct conversion of sunlight to the electricity without any devices like heat engine [103]. PV systems include different components such as: cells, mechanical and electrical connections and current regulating systems. In these systems the amount of delivered electrical power when the sun is located in a position direct to head of system in a clear day, is named as peak kilowatts (kWp).

There are different types of solar PVs including: silicon (consist of amorphous silicon and crystalline silicon), Cadmium telluride (CdTe) and Cadmium sulphide (CdS), Organic and polymer cells, Hybrid photovoltaic cell and Thin film technology which some of them are explained below;

Amorphous silicon

As most popular thin-film solar cells and amorphous solar cells with cell efficiency between 5-7 % are widely used. The efficiency of cell rises to 8-10 % when it is designed based on the triple junction. The main weakness point of this type of solar cells is degradation. There are different kinds of amorphous solar cells such as amorphous silicon carbide (a-SiC), amorphous silicon germanium (a-SiGe), microcrystalline silicon (c-Si) and amorphous silicon-nitride (a-SiN). Recently, some studies report the efficiency around 13 % for this type of solar cells [104].

Crystalline silicon

In compared with other type of silicon solar cells, crystalline silicon solar cells have more efficiency. These solar cells have some advantages like small consumption of materials when they are compared with other types. Their efficiency is at the range between 14-19 %. Studies show that new generation of silver cells formed with single crystal silicon solar cells have advantages like less consumption of silicon (about 10-20 times) in compared with conventional types of crystalline solar cells [105].

Cadmium telluride (CdTe) and cadmium sulphide (CdS)

Cadmium telluride solar cells are formed from a thin film of CdTe for absorbing and converting the sunlight to electricity. This kind of solar cell is developing very fast and at the present state, it is the second most popular solar cell in the world after silicon solar cells. The main advantage of CdTe solar cells is the low cost of fabrication for panels. The cost of electricity for CdTe panels is less than 1.00 USD per Watt. Some specifications like ease of manufacturing, good match with sunlight and availability of Cadmium (Cd) make these solar cells as the main candidates for future applications.

It is about two decades that polycrystalline thin film CdS/CdTe solar cells have attracted so much attention so that they are considered as main candidates for large scale application in the conversion of solar energy to electricity [106-108]. Fabrication methods of polycrystalline CdS/CdTe layers play the key role in cell efficiency and also cost of cell. Recent progress in fabrication of these solar cells has increased the efficiency of CdS/CdTe cells around 21% [109].

Copper indium gallium selenide (CIS/CIGS) solar cells

With an efficiency around 14 %, Copper Indium Selenide (CIS) solar cells are formed by an absorber layer of $CuInSe_2$ on a plain or flexible metal backing. Their cost of manufacturing is less than Si solar cells. Maximum output power of this kind of thin film solar cells is 25 Watts (3.9 V and 64 mA).

Copper Indium Gallium Selenide (CIGS) solar cells are formed by a thin layer of copper indium gallium selenide $Cu(In, Ga)Se_2$ as absorber layer. Like CIS solar cells they have lower cost in compared with Si solar cells and their efficiency is up to 10%. Maximum output power of this generation of solar cells is 3 watts.

2.1.2 Wind energy

Wind energy can be considered as one of the main sources of renewable energy. Wind energy has a huge technical potential for electricity production which is from 20000 TWh/year to 125000 TWh/year. This potential is more than six times of global electricity production in 2009 which is about 20000 TWh based on IEA report. Even though the potential of wind energy depends on location, potential of most regions is enough to produce electricity. Figure 1.5 shows the map of global wind resources.

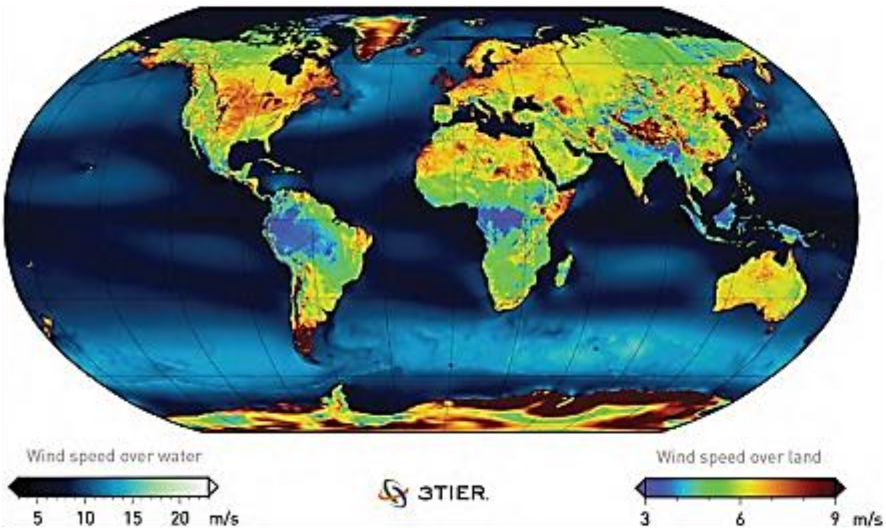


Figure 1.5 : Global wind energy source based on velocity [110].

For wind energy conversion there are two types of wind turbine technology including onshore and offshore wind turbines which are described in following sections.

2.1.2.1 Onshore

Onshore wind turbines have developed in size from 1980. In the early 1980s, the capacity of turbine was 50 kW while current offshore turbines are developing to 5 MW. Onshore wind turbines are very important technologies between renewable energy conversion technologies due to their cost- effective advantages. Another advantage of onshore technologies is being close to electric grids that decrease the environmental impacts in term of constructing new electricity transmission grid. Disadvantages of this technology are noise pollution, visual pollution and harm to birds. The cost of this technology is lower than offshore technology.

2.1.2.2 Offshore

Offshore technology is installed both right off the coast and in the sea. In the first case there are placed on platforms which are made from concrete and are extended to the bottom of sea. In the second case they are developed in the sea using floating platforms. Offshore technology is one of the most expensive renewable energy conversion technologies. In compared with fossil fuels, offshore technology is 90 % more expensive which is due to technical difficulties related to their connection to electricity grid. For developing this technology, developing new materials and new technologies are required which they need more investment on this type of wind turbines.

2.1.3 Bioenergy

Energy from sun is stored in the plants by photosynthesis mechanism. Rate of this energy source is seven times the current global rate of energy use which is 500 Ej/year. This is while less than 2 % of this energy is used for human demands. About 10 % of current global primary energy consumption is from biomass (Figure 1.6). In developing countries, biomass is the most traditional source of energy so that people use firewood for different purposes like cooking and heating.

Biomass can be used in some process for producing fuel, power and some products that are made by fossil fuels normally. There are some advantages of biomass utilization including decreasing the greenhouse gas emission, reducing the dependence to foreign oils, producing green fuels for vehicles and etc. through different conversion technologies like pyrolysis, gasification and biodiesel production by microalgae cultivation.

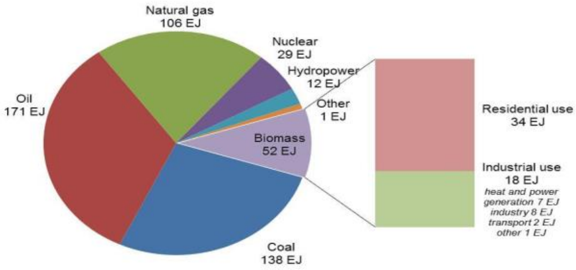


Figure 1.6 : Share of biomass in global primary energy supply. [9]

2.1.4 Ocean energy

About 71 % of Earth's surface is covered by oceans. The ocean absorbs sun's lights so that the temperature of upper layers increases to 25 ºC. Also due to gravity of moon, an alternate rising and falling of the sea happens which is known as tide. Mentioned phenomena are the source of electricity generation through ocean. Electricity generation technologies through ocean are tidal power, wave power, ocean thermal energy, ocean current, ocean winds and salinity gradient energy. The last technology is due to difference of salinity between diluted and concentrated solutions when a body of fresh water (river) runs into sea water. Figure 1.7 [111] shows the locations with potential for electricity generation through ocean energy. There are different conversion technologies for electricity generation using ocean including tidal barrages, tidal turbines, ocean thermal energy plants, reverse electrodialysis, pressure retarded osmosis and etc. Many of mentioned technologies are not effective in terms of cost.

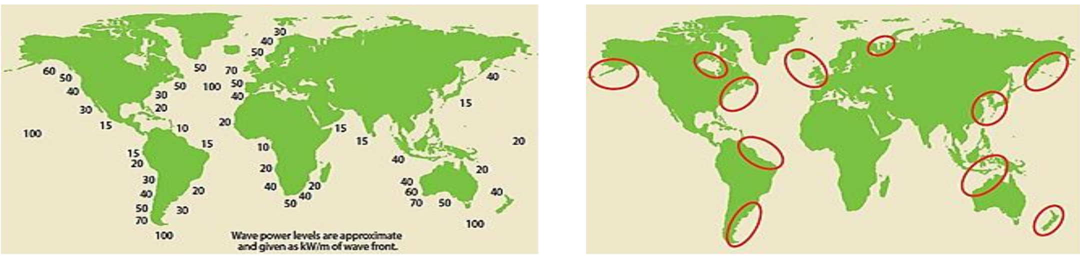


Figure 1.7 : Left: Global distribution of ocean energy, Right: Potential locations for traditional tidal power [111].

2.1.5 Geothermal energy

The source of geothermal energy is the heat which is from earth. The first geothermal power plant opened in 1960 in the United States and this source of renewable energy has a high potential in some countries like Japan, United States and Italy. In this technology, United States is the leading country in the world. Annual generated electricity in the United States using geothermal technology is 15 billion kilowatt hours of power. This value can be compared with burning about 25 million barrels of oil or 6 million tons of coal per year. Figure 1.8 shows the global map of geothermal energy and indicates places with high potential of geothermal energy technologies.

Some advantages of geothermal energy are low emission level, smaller land footprint and reliable output in compared with other renewable energy sources. Based on the report published by International Energy Agency (IEA), geothermal energy deployment will reduce between 700-800 million tons of CO_2 in 2050. Between 1999-2004 electricity production through geothermal energy technology increased 16% with annual growth of 3%. Direct use has in the mentioned period of increased 43% with annual growth rate of 7.5 %. The United States, Philippines, Mexico, Indonesia, Italy and Japan are the major countries in terms of electricity production through geothermal energy conversion technology.

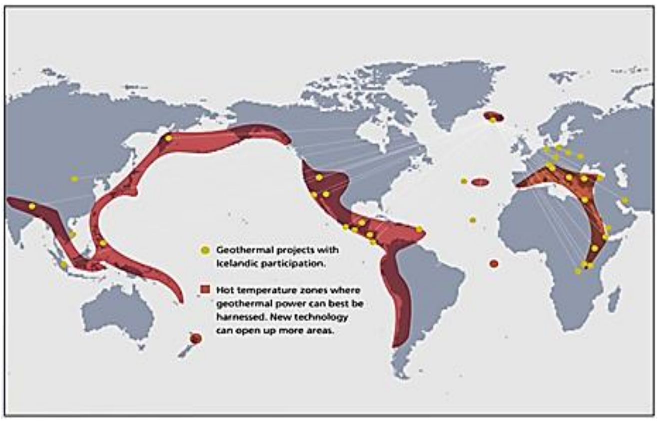


Figure 1.8 : Global map of potential locations for geothermal energy.

2.1.6 Hydropower

Providing around 16% of global electricity demand and more than 4/5 of global renewable electricity, hydropower can be considered as the world's largest renewable energy source. Hydropower provides more than 90% of electricity demands in more than 25 countries. About 99.3% of electricity supply in Norway depends on hydropower while in 12 countries about 100% of produced electricity depends on hydro. In global scale, Canada, China and the United States are the countries which have the largest hydropower generation capacity. In 2009, about 11000 hydropower power plants were operating and generating the electricity in 150 countries. The total global electricity production by hydropower reached to 3329 TWh in 2009 which it is about 16.5% of the global electricity supply in the same year. Mentioned value is equal with 85% of the global renewable electricity production. Figure 1.9 shows the hydropower generation in different regions in the last decades. Global installed capacity of this technology was between 926 and 956 GW based of evaluations. Based on scenario presented by IPCC in 2011, hydropower generation will increase 35 % by 2030 and 59% by 2050.

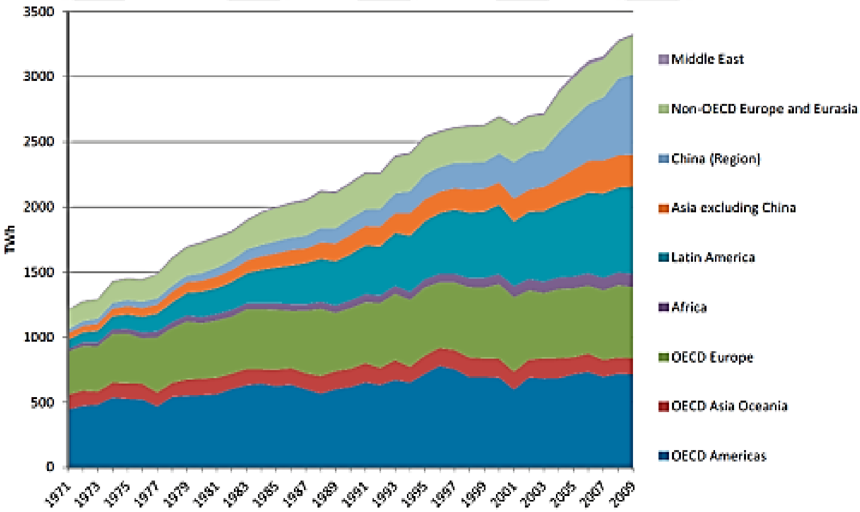


Figure 1.9 : Hydropower generation between 1971- 2009 [9].

2.2 100% Renewable Energy World

Reaching to a renewable world based on 100 % renewable energy sources has attracted attentions recently. Employing renewable energy technologies is necessary for providing future demands of electricity and for preventing from negative effects on the environment [112]. Based on a case study on Denmark, reaching to a 100% renewable electricity is feasible by 2050 using energy sources like biomass and combination of wave, wind and solar power [113]. In the mentioned study the feasibility of reaching to 50 and 100 % renewable society for Denmark is investigated for 2030 and 2050 respectively using simulations of energy demands. In another study reaching to a 100 % renewable society for long term (2050) is possible by using a designed energy system but there are some challenges like the balance between large consumption of biomass and large amount of electricity for purposes like direct use or for producing synthetic fuel [114]. Based on the results of another study by Connolly and Mathiesen [115] related to Ireland, reaching to a 100 % renewable energy system is feasible technically. The possibility of 100 % renewable electricity systems is investigated through applying another model used for more than 160 countries investigating hourly electric load demand and considering wind energy (off shore), PVs and CSP (Concentrates solar power) as energy sources [116]. Results of this study indicates the feasibility of supplying 100% renewable electricity in global scale. Jacobson and Delucchi [97] investigated all the required global demand of energy for different applications such as electric power, transportation, heating, cooling and etc., by wind, water and sun (WWS). In this study the total global demand for energy in 2030 is considered about 11TW in 2030. To obtain an exact evaluation about criticality of materials and metals utilized in renewable energy technologies in 2030 and 2050, some background about renewable energy conversion technologies, resources and reserves, long term scenarios related to renewable energy technologies deployment are necessary to be discussed. In the following sections these topics are investigated;

2.2.1 Renewable energy scenarios

Developing sustainable energy systems consists of three main technological challenges including: saving the energy on demand side, reducing waste by improvement in efficiency of energy systems, and replacing the fossil fuel by renewable energy sources [113]. To imagine 100% renewable energy world, it is necessary to understand the energy demands for long terms periods like 2030 and 2050. In other words, utilizing some roadmaps for future energy demands and also in case of renewable energies, share of break down technologies are essential to be understood. Mentioned and related breakdown technologies are: Solar energy (PVs, CSP and solar thermal energy), Wind energy (onshore and offshore), bioenergy (heat, fuel and electricity), geothermal energy (heat and electricity), hydro power and ocean energy. In this study for determining our demands of renewable energy (in 2030 and 2050) and also share of different breakdown technologies, the following roadmaps are considered.

2.2.1.1 IPCC

Intergovernmental Panel on Climate Change (IPCC) has investigated 164 long-term scenarios. All of the investigated scenarios cover a range for CO_2 concentration (350-1050 ppm) in the atmosphere of the earth by 2100. Based on the mentioned scenarios, five categories for level of CO_2 in the atmosphere of the earth are considered by 2030 and 2050. These categories are: category one (<400 ppm), category two (400-440 ppm), category three (440-485 ppm), category four (485-600 ppm) and Baselines. Deployment of renewable energies for each category is different in the mentioned scenarios and based on IPCC report, the highest levels of renewable energies deployment are presented by scenarios which have less emission of CO_2 to the environment. In scenarios with the highest level of renewable energy technologies 77% of world's demand for energy (400-420 EJ) will be provided by renewable energy technologies in 2050. Based on the long term scenarios in this report, solar PVs have major source of energy in 2050 with about 20% share in total required energy. Wind energy and bioenergy can be considered as other major sources of energy in 2050 with annual share about 16% and 15% respectively. Based on scenario of IPCC the median value of renewable energy deployment levels are 139 Ej/year and 248 EJ/year in 2030 and 2050 respectively for the scenarios stabilizing atmospheric carbon dioxide concentration at a level of less than 440 ppm. The highest level of renewable energy deployment in these scenarios are 252 Ej/year and 428 Ej/year in 2030 and 2050 respectively.

2.2.1.2 WWF

Based on the report published by World Wide Fund for Nature (WWF) in 2011, reaching to a 100% renewable energy world is possible considering the potential of renewable energy sources and also high deployment of renewable energy conversion technologies. In this report the energy scenario is created by Ecofys which is a leading consultancy in the fields of renewable energy and carbon efficiency, energy systems and markets and finally energy and climate policy. In WWF-2050 scenario, the total energy demand in 2050 is considered about 250 EJ. In this roadmap bioenergy consisting different applications like fuel, heat and electricity has major share between other renewable energy sources. Also solar energy including PVs, CSP and solar thermal can be considered as a main source of energy in 2050.

2.2.1.3 IEA-HiREN

This scenario is presented by International Energy Agency (IEA) considering about 71 % of global electricity will be provided by renewable energy technologies in 2050. It is important to keep in mind that this value may fluctuate about 32% due to possibility of changes in the share of technologies related to wind energy (onshore and offshore), ocean energy in 2050. Based on this scenario, in 2050 the share of solar PVs will be dominant as the renewable energy technology in global electricity production with an annual share of 25% generating about 24 EJ per year in 2050. This scenario is not 100% renewable and other conventional technologies like natural gas, nuclear energy, coal with carbon capture and storage (CCS) will provide energy demands in 2050. All in all, the share of conventional technologies in this scenario is not very high compared to renewable energy technologies.

2.2.1.4 IEA-HiREN

This roadmap is based on data presented by Energy Technology Perspectives (ETP) so that the 2 Degree Scenario (2DS) is a main focus of ETP. The 2DS considers the target of reducing and cutting the CO_2 emissions of energy technologies and related processes by almost 60 % (compared to 2012) by 2050 and continuing this roadmap after mentioned time target (2050). This scenario has a close similarity to another scenario known as WEO 450 aiming to reduce the concentration of greenhouse gases (GHG) and CO_2 at the level of 450 ppm in the atmosphere of earth. The scenario is not totally renewable but it considers the renewable energy sources as dominant energy sources in 2050 providing about 57 % of global energy demands. The total amount of required energy for 2050 is determined about 300 EJ/year. Based on this roadmap bioenergy is the main source of energy in 2050. After bioenergy other renewable energy sources like hydropower and nuclear energy are major sources of energy in 2050 based on IEA-2DGS scenario.

Depending on different parameters considered in every scenario, magnitude of renewable energy technologies are different in long term scenarios. Between long term roadmaps, IPCC 2050 has considered maximum deployment potential of renewable energy technologies for 2050 which is about 428 EJ in 2050. The scenario considers a share about 77% for renewable energy technologies to provide global energy demands. Magnitude of each renewable energy technology in different scenarios is presented in figure 1.10. After IPCC 2050, the maximum deployment potential of renewable energy technologies in 2050 is considered to be 295, 252, 248 and 151 EJ per year by IEA-2DS, IPCC 2030, WWF 2050 and Hi-REN, respectively.

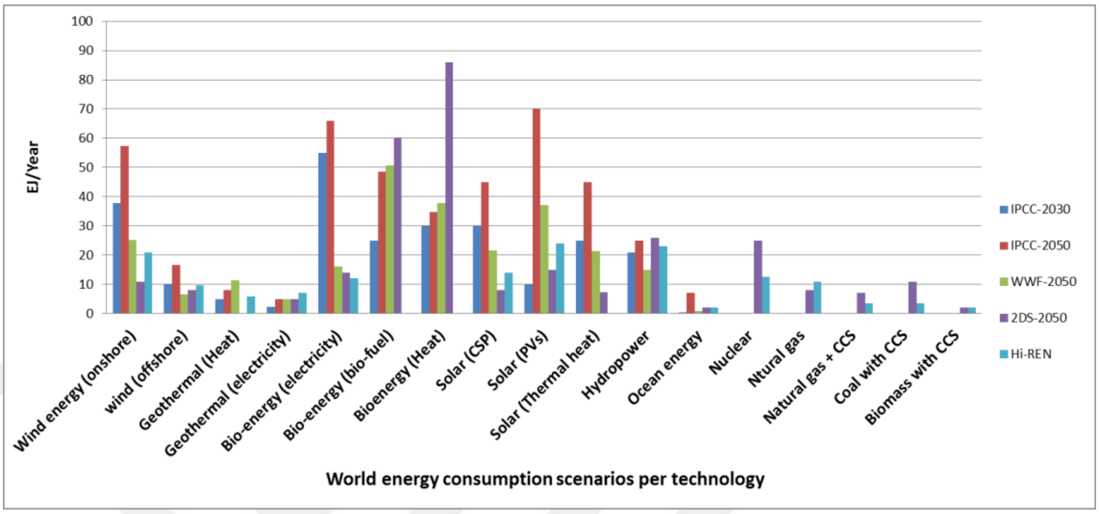


Figure 1.10 : Share of break down technologies related to renewable energies in different scenarios

3. RESULTS AND DISCUSSION

3.1 Inventory Step

In this study availability of 35 resources including different metals and water were analyzed through the methodology which mentioned in the method section. As it was mentioned before, in the first step, list of materials used in renewable energy technologies and available in SimaPro 7 software (database of Eco invent information) were employed. Thus, a table of metals and material used in different renewable energy technologies was prepared (Table 3.1). In this table the amount of consumed metals in each technology is presented based on $kg.kWh^{-1}$ while this value for water was presented based on $m^3.kWh^{-1}$. Data presented in Table 3.1 were used in all the calculations related to the amount of metal required in 2030 and 2050. In other words, this table is considered as input source of our calculations in this study. Investigated renewable technologies are solar energy (PVs, CSP, thermal heat), wind energy (off shore and on shore wind turbines), geothermal (heat and power), bioenergy (bio-fuel, heat and power) and hydro (hydropower and ocean energy).

3.2 Screening Steps

Using the data presented in table 3.1 mass balance of demands related to renewable energy technologies in 2030 and 2050 (for reaching a renewable energy plant) was investigated employing several several roadmaps. The results of calculations are compared with current recognized resources and reserves of metals in the world.

The results of calculations in terms of metal consumption based on reserves/ resources until 2050 are presented in figures 3.1 and 3.2. In mentioned figures reserves are divided to 35 in order to indicate the availability of reserves/ resources until 2050. In mentioned figures to illustrate all the metals and materials, the logarithm scale is considered for indicating consumption and “reserves/ resources until 2050”.

Table 3.1 : Extracted LCA data for all the metals and materials used in renewable energy technology (kg.kWh^{-1}).

Metal	Solar PV (CdTe)	Solar PV (CIS)	Solar PV (a-Si)	Solar energy (CSP)[98]
Aluminium (Al)	0.0010068	0.001181	0.0021704	2.08E-04
Borodine (Br)	6.4221E-09	1.4532E-09	1.4899E-09	0
Cadmium (Cd)	0.00026592	0.00026903	6.7082E-06	0
Chromium (Cr)	0.000022282	0.000027264	0.000074929	0
Cobalt (Co)	7.9495E-11	7.0977E-11	8.1359E-11	0
Copper (Cu)	0.000426954	0.000291532	0.000319982	4.13E-04
Fluorspar	0.000010589	9.1196E-06	0.000080443	0
Gallium (Ga)	1.6348E-13	4.7246E-06	7.6501E-14	0
Gold (Au)	1.00377E-08	9.9854E-09	9.92934E-09	0
Indium (In)	3.4792E-09	0.000037212	0.000010035	0
Dysprotium (Dy)	0	0	0	0
Lead (Pb)	1.4699E-06	1.3396E-06	1.5003E-06	0
Lithium (Li)	3.0387E-11	6.8519E-12	7.0175E-12	0
Magnesite	0.000010169	0.000013038	0.000037173	0
Magnesium (Mg)	1.0076E-07	0.000012652	0.000044521	0
Manganese (Mn)	7.6732E-06	0.000018617	0.000064754	0
Molybdenum (Mo)	6.73237E-06	1.32385E-05	6.21175E-06	0
Neodymium (Nd)	0	0	0	0
Nickel (Ni)	5.23088E-05	6.45555E-05	0.000174278	2.46E-06
Palladium (Pd)	3.5978E-11	3.01053E-11	2.86124E-11	0
Phosphorus (P)	1.67768E-06	1.29996E-06	1.26237E-06	0
Platinum (Pt)	2.28982E-12	3.85781E-12	2.03633E-12	0
Potassium (K)	0.000021037	0.000020358	0.000020363	0
Rhenium (Re)	5.4463E-13	4.3348E-13	4.2409E-13	0
Rhodium (Rh)	9.3422E-13	1.08019E-12	8.0907E-13	0
Silver (Ag)	1.13735E-06	3.50515E-07	3.7288E-07	2.53E-06
Sodium (Na)	0.001265428	0.001025113	0.000377066	0
Sulfur (S)	3.5848E-06	6.7365E-06	2.8079E-06	0
Tantalum (Ta)	6.3639E-07	6.3636E-07	6.3628E-07	0
Tellurium (Te)	1.3529E-07	1.7265E-08	2.0644E-08	0
Tin (Sn)	2.2053E-06	6.5105E-06	0.000007421	0
Titanium (Ti)	4.00212E-06	3.42571E-06	2.3201E-05	0
Water	0.000480081	0.000490493	0.000432647	4.70E-03
Zinc (Zn)	0.00001786	0.000030194	0.00006715	0
Zirconium (Zr)	1.0171E-07	1.0165E-07	1.0157E-07	0

Table 3.1 (continues): Extracted LCA data for all the metals and materials used in renewable energy technology (kg.kWh^{-1}).

Metal	Solar energy (Thermal heat)[115]	Wind Turbines (offshore)	Wind Turbines (Onshore)	Geothermal (Heat and Power)[116]
Aluminium (Al)	0.00225	0.000022428	0.000021432	3.53E-06
Borodine (Br)	0	2.0643E-11	1.8223E-11	0
Cadmium (Cd)	0	1.6243E-09	2.1388E-09	0
Chromium (Cr)	0	0.00015261	0.00016042	8.66E-07
Cobalt (Co)	0	1.0766E-11	6.33E-12	0
Copper (Cu)	0.00765	3.96751E-05	0.000039279	7.31E-06
Fluorspar	0	4.9566E-06	5.1356E-06	0
Gallium (Ga)	0	1.6407E-14	1.4451E-14	0
Gold (Au)	0	2.13758E-11	1.57077E-11	0
Indium (In)	0	2.7884E-11	3.6363E-11	0
Dysprotium (Dy)	0	1E-2	0	0
Lead (Pb)	0	0.00001948	1.1767E-07	0
Lithium (Li)	0	6.1055E-14	5.3759E-14	0
Magnesite	0	0.000037013	0.000030911	0
Magnesium (Mg)	0	4.7876E-11	4.1606E-11	0
Manganese (Mn)	0	0.000018304	0.000019023	2.44E-08
Molybdenum (Mo)	0	1.18532E-06	1.20305E-06	5.72E-08
Neodymium (Nd)	0	0.2[95]	0	0
Nickel (Ni)	0	0.000362704	0.000377483	7.77E-07
Palladium (Pd)	0	3.22069E-12	2.39155E-12	0
Phosphorus (P)	0	1.0548E-07	9.1737E-08	0
Platinum (Pt)	0	2.77723E-13	4.8276E-13	0
Potassium (K)	0	1.8461E-07	2.1512E-07	0
Rhenium (Re)	0	2.4522E-14	2.0028E-14	0
Rhodium (Rh)	0	9.2906E-14	7.1704E-14	0
Silver (Ag)	0	6.16445E-11	4.53854E-11	0
Sodium (Na)	0	0.000144315	0.000105445	0
Sulfur (S)	0	6.0419E-06	5.3622E-06	0
Tantalum (Ta)	0	2.1856E-11	1.6227E-11	0
Tellurium (Te)	0	3.0032E-12	2.2355E-12	0
Tin (Sn)	0	1.103E-08	2.4586E-08	0
Titanium (Ti)	0	1.17491E-06	1.02661E-06	0
Water	0	0.000156534	0.000113883	0
Zinc (Zn)	0	5.0795E-07	3.9946E-07	0
Zirconium (Zr)	0	2.865E-11	2.1077E-11	0

Table 3.1 (continues): Extracted LCA data for all the metals and materials used in renewable energy technology (kg.kWh^{-1}).

Metal	Bioenergy (biofuel)[117]	Bioenergy (Heat)	Hydropower	Ocean Energy[118]
Aluminium (Al)	0.00048158	0	1.7049E-06	0
Borodine (Br)	0.00014103	0	2.857E-12	0
Cadmium (Cd)	2.9649E-07	0	3.5885E-10	0
Chromium (Cr)	0.0001325	0	0.000015556	0
Cobalt (Co)	3.0874E-09	0	6.7062E-12	0
Copper (Cu)	0.000145942	0	3.63175E-07	0.0268
Fluorspar	0.000091468	0	4.6972E-08	0
Gallium (Ga)	2.1127E-13	0	4.021E-15	0
Gold (Au)	7.06465E-09	0	3.73417E-12	0
Indium (In)	4.9511E-09	0	6.18E-12	0
Dysprotium (Dy)	0	0	0	0
Lead (Pb)	0.000014184	0	2.4863E-08	0
Lithium (Li)	3.2151E-07	0	1.2446E-14	0
Magnesite	0.000057276	0	7.4344E-06	0
Magnesium (Mg)	2.3685E-09	0.0038	9.8035E-12	0
Manganese (Mn)	0.00002405	0	5.7861E-06	0
Molybdenum(Mo)	2.80658E-06	0	1.95176E-07	0
Neodymium (Nd)	0	0	0	0
Nickel (Ni)	0.000364176	0	3.9162E-05	0
Palladium (Pd)	3.9423E-10	0	1.36631E-12	0
Phosphorus (P)	0.005292744	0.0099	1.59134E-08	0
Platinum (Pt)	1.82608E-10	0	8.7787E-14	0
Potassium (K)	0.046737	0.0082	1.395E-09	0
Rhenium (Re)	1.7406E-12	0	1.3142E-14	0
Rhodium (Rh)	3.82087E-12	0	4.0196E-14	0
Silver (Ag)	1.89E-08	0	1.09289E-11	0
Sodium (Na)	0.002544159	0	2.42378E-06	0
Sulfur (S)	0.000014755	0.0022	5.5632E-10	0
Tantalum (Ta)	6.8604E-09	0	3.8983E-12	0
Tellurium (Te)	9.3038E-10	0	5.3839E-13	0
Tin (Sn)	4.7021E-07	0	1.5013E-09	0
Titanium (Ti)	3.43013E-05	0	4.51462E-08	0
Water	0.4767[119]	0.4	4.73016E-05	0.22
Zinc (Zn)	0.00013357	0	1.3072E-07	0.0003
Zirconium (Zr)	9.4178E-09	0	5.0163E-12	0

Table 3.1 (continues): Extracted LCA data for all the metals and materials used in renewable energy technology (kg.kWh^{-1}).

Metal	Bioenergy (Electricity)
Aluminium (Al)	0.000011004
Borodine (Br)	2.0042E-11
Cadmium (Cd)	4.9518E-09
Chromium (Cr)	0.000012768
Cobalt (Co)	0.0032426
Copper (Cu)	0.000044524
Fluorspar	3.0726E-06
Gallium (Ga)	2.0274E-13
Gold (Au)	6.19649E-11
Indium (In)	9.2606E-11
Dysprotium (Dy)	0
Lead (Pb)	1.6679E-06
Lithium (Li)	7.0583E-14
Magnesite	0.0000298
Magnesium (Mg)	3.8795E-10
Manganese (Mn)	6.7766E-07
Molybdenum (Mo)	6.7859E-07
Neodymium (Nd)	0
Nickel (Ni)	3.58005E-05
Palladium (Pd)	2.02037E-09
Phosphorus (P)	4.6163E-07
Platinum (Pt)	9.9603E-09
Potassium (K)	2.3249E-08
Rhenium (Re)	2.1711E-13
Rhodium (Rh)	1.75476E-09
Silver (Ag)	2.13741E-10
Sodium (Na)	8.96376E-05
Sulfur (S)	1.3562E-08
Tantalum (Ta)	7.4103E-11
Tellurium (Te)	1.0547E-11
Tin (Sn)	1.593E-07
Titanium (Ti)	1.7516E-06
Water	0.000443823
Zinc (Zn)	7.6565E-07
Zirconium (Zr)	8.4568E-11

For some metals which there was not any exact data related to proven reserves, value of resources were employed in the calculations. This approach also was applied for metals without exact assessment about their resources so that recognized reserves were considered in the calculations. Based on USGS data, there is not an exact assessment about the proven reserves and resources of magnesium so that it is indicated as an abundant metal. Thus, figures 3.1 and 3.2 don’t include this metal. In the case of rhenium, due to low amount of resources and reserves, all the calculations of reserves/ resources and also consumption are based on kg per year in order to prevent negative values in the figures. As it is depicted in the figures 3.1 and 3.2 the criticality criteria of metals and materials increases when the consumption is higher than reserves/ resources until 2050. The degree of criticality of metals and materials is proportional with their distance from *y=x* line (blue line in the figure) so that more distances indicate higher consumption in compared with reserves/ resources. In other words, the critical metals are some of them that are above the *y=x* line while the metals and materials with lower criticality are in the below region of *y=x* line. The blue line is the interface between critical and safe zone for investigated metals. In other words, metals on this line have almost the equal amounts of consumption and reserves/resources in 2030 or 2050. The comparison of these figures indicates that some metals like copper and potassium are moved to the region below *y=x* line. This can be referred to huge resources of these metals compared to recognized reserves.

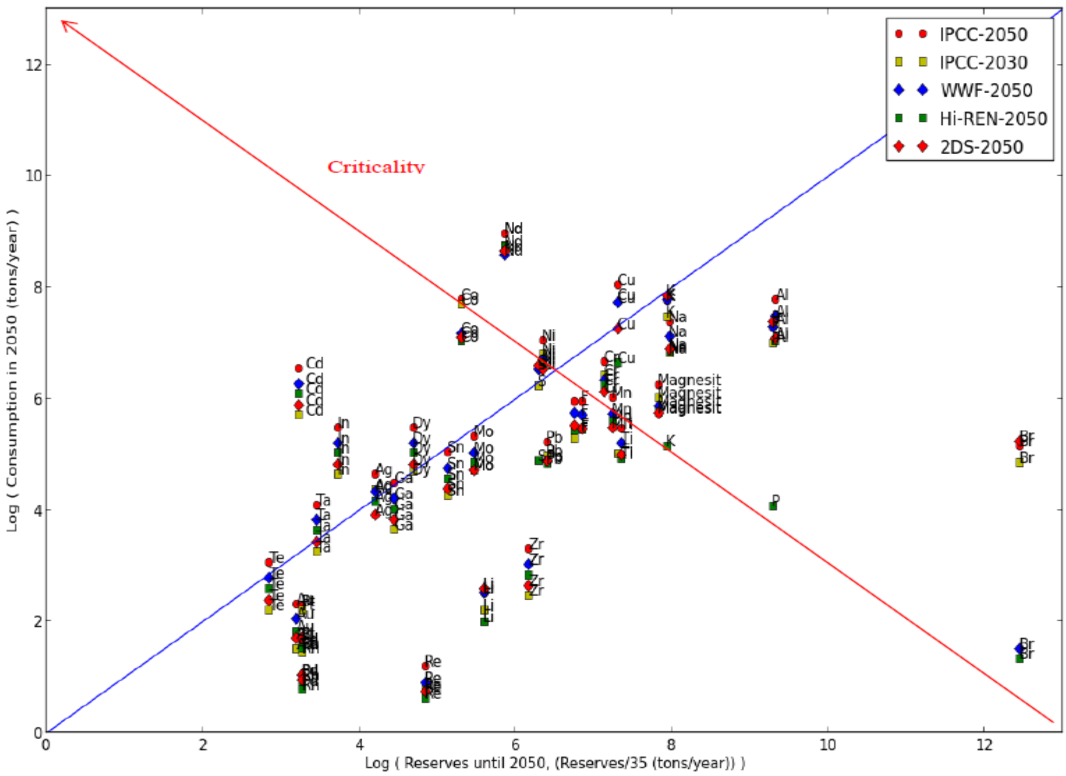


Figure 3.1 : Consumption of metals and materials in compared with current reserves until 2050.

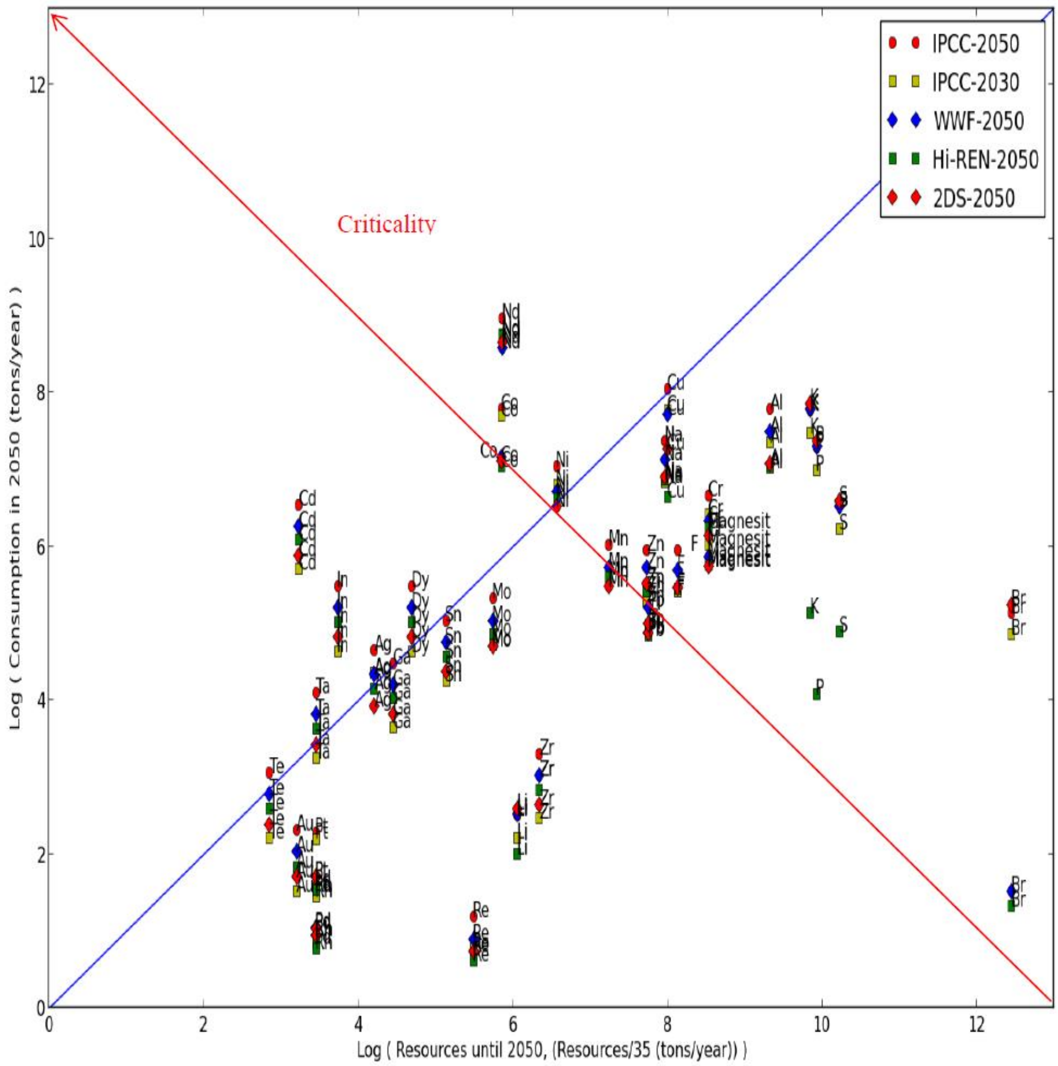


Figure 3.2 : Consumption of metals and materials in compared with current resources until 2050.

3.3 Screening Steps

Water is another important resource which is consumed in different renewable energy conversion technologies. In this study the consumption of water is analyzed and its usage in processes like cooling is ignored. In other words, in this study water consumption is referred to the amount of water which is used in different technologies and it does not include any recycling. The global fresh water withdrawal and the share of different sectors in water consumption are presented in figure 3.3.

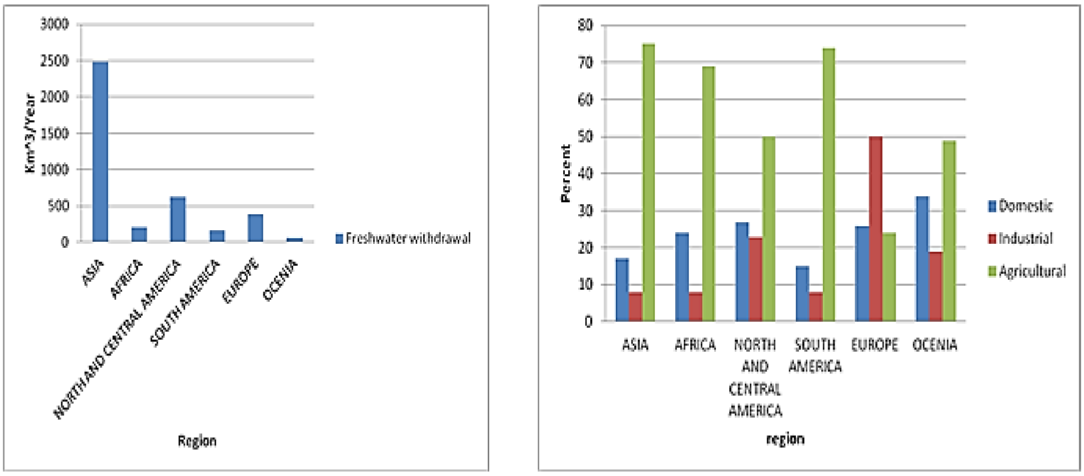


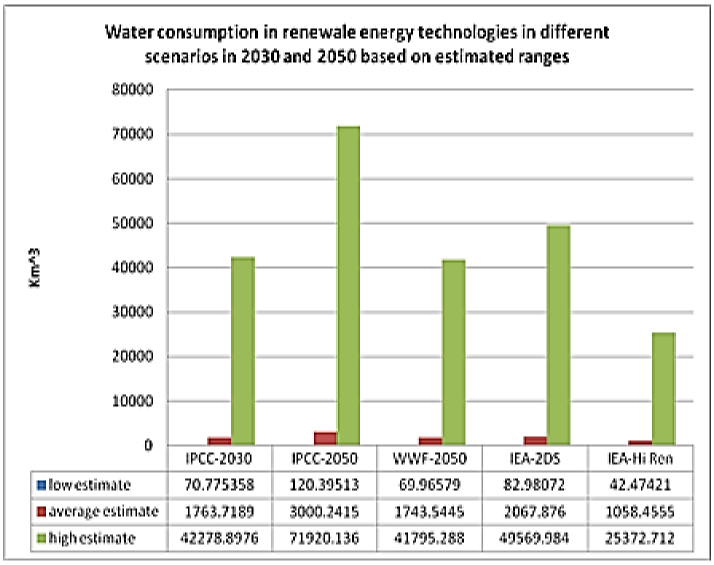
Figure 3.3 : Global withdrawal of fresh water in different region and share of consumer sectors in 2011[10].

Water consumption in the renewable energy technologies is analyzed by Pfister et al. [122]. In this study three categories including low, medium and haigh estimations are considered for water consumption in the renewable energy technologies as presented in Table 3.2. As it is clear, hydropower technology consumes the high amount of water in compared with other renewable energy technologies.

Table 3.2 : Suggested ranges for water consumption in the renewable energy technologies [122].

Water consumption	Average Estimate (km^3/EJ)	Low Estimate (km3/EJ)	High Estimate (km3/EJ)
Hydropower	6.95	0.28	166.7
Alternative energies	0.055	0.011	1.22
Total (km^3/EJ)	7.005	0.2811	167.92

Considering different energy demands in near and long term scenarios, water consumption was calculated based on presented data in Table 3.2 Obtained results were compared with results of this study. Water consumption in different scenarios is presented in figure 3.4. Based on this figure, there is a high difference between high, average and medium estimations in water consumption.



	IPCC-2030	IPCC-2050	WWF-2050	IEA-2DS	IEA-Hi Ren
low estimate	70.775358	120.39513	69.96579	82.98072	42.47421
average estimate	1763.7189	3000.2415	1743.5445	2067.876	1058.4555
high estimate	42278.8976	71920.136	41795.288	49569.984	25372.712

Figure 3.4 : Water consumption calculation in different renewable energy scenarios based on estimations done by Pfister et al [122].

Results of our this thesis are presented in Figure 3.5 which are in acceptable range with calculations done using the estimated values presented in Table 3.2. In other words, results of this thesis for calculating water consumption are between low and medium estimates of Pfister et al [122] that are presented in Figure 3.4.

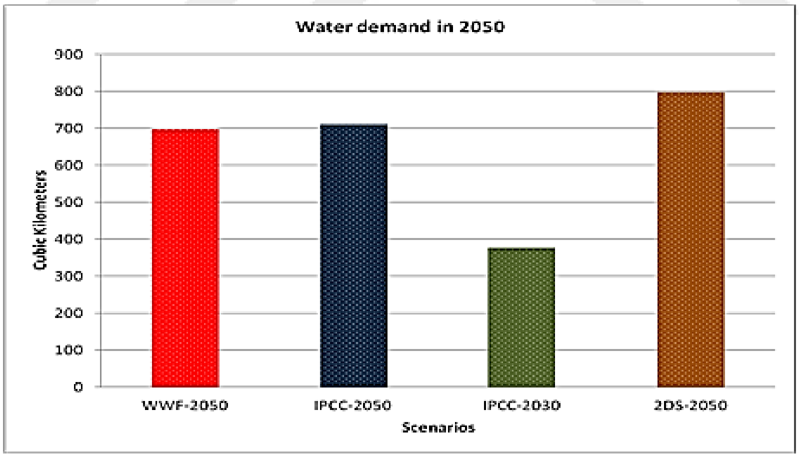


Figure 3.5 : Water consumption of renewable energy technologies in new term and long term periods based on different scenarios.

Studies show that global sustainable water in 2025 will be around 37100 $km3.year^{-1}$ [123]. Considering estimated sustainable water in 2050, renewable energy technologies won't face with a shortage of water in 2030 or 2050 according to results of this thesis which are presented in Figure 3.5.

3.4 Effect of Accumulation

To obtain a reliable assessment about availability of metals, it is necessary to consider the value of recycling rate for each metal. Also it is important to consider consumption rate and production rate of metals during investigated period of time. All of mentioned parameters are considered in the accumulation calculations as are discussed in the method section (section 1.4). Accumulation in n^{th} year indicates the available metals which are stored within previous years. Based on results, this value plays a very important role for metals like Co and Ni so that accumulation will support required metals in 2030 and 2050 for a 100% renewable energy scenario.

For example in case of copper, results indicate that required amount of this metal in 2050 based on IPCC 2050 will be around 155 million tons which is about 22 % of global resources of copper based on data presented by USGS. This is while the accumulation calculations show about 65 million tons of stored copper in 2050 which can support the demands for this metal in 2050. Figure 3.6 shows the accumulation and required amount of copper in 2050.

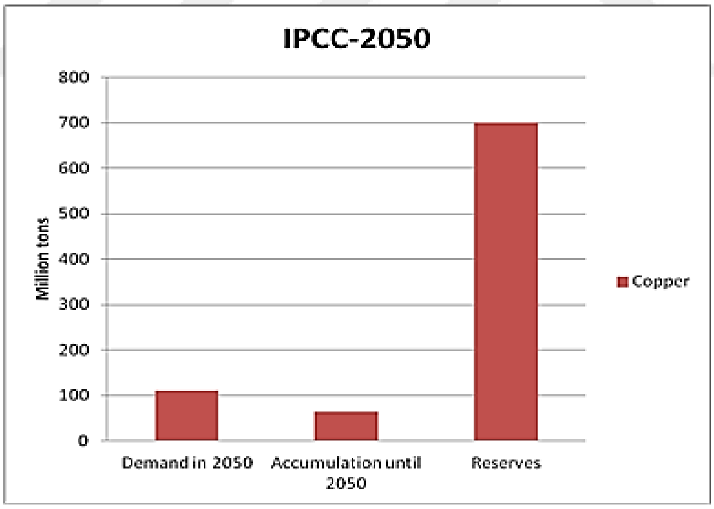


Figure 3.6 : Accumulation, Demand and Reserves of copper.

Figure 3.7 indicates a simple chain of processes and results of this project. As it is presented in this figure, after inventory, first screening and second screening steps were completed, the final metals which will create a wall against reaching to a 100% renewable energy world were detected.

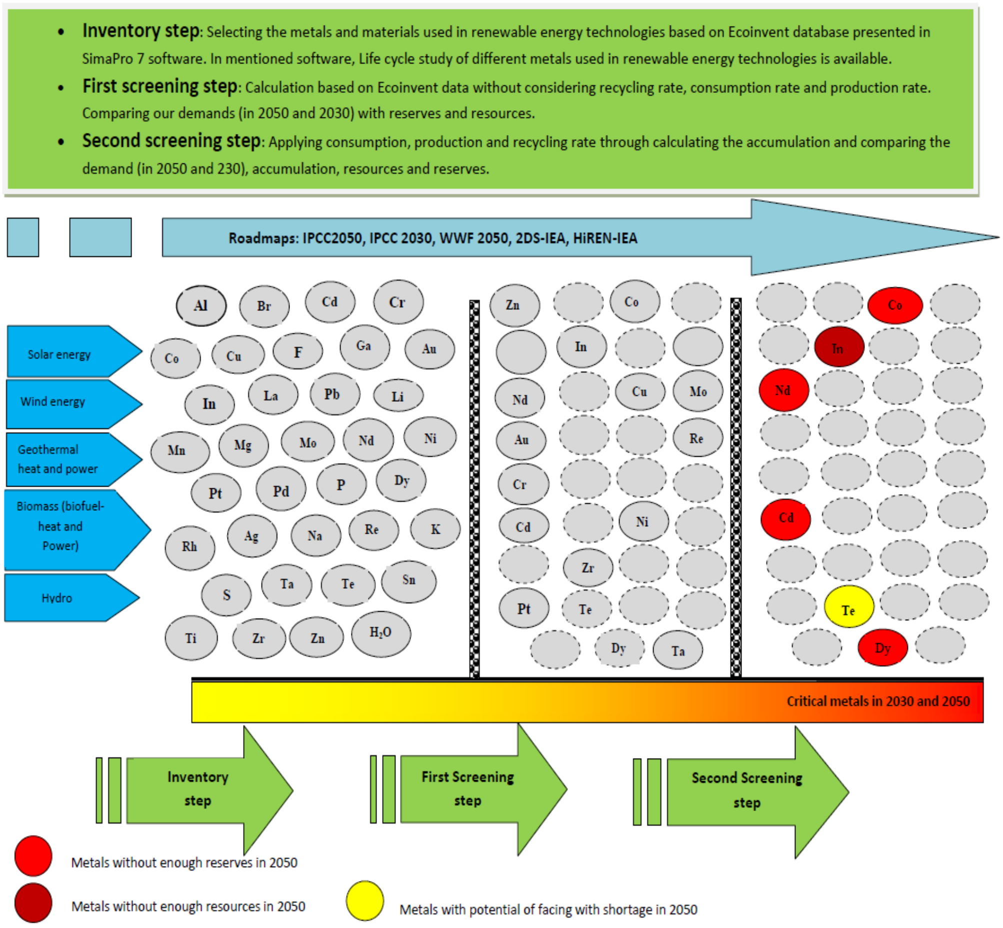


Figure 3.7 : The chain of selecting and screening critical resources of renewable energy technologies in 2030 and 2050.

3.5 Critical Resources

Considering the accumulation some of the investigated 35 metals were categorized as critical metals. Some metals will face a shortage in resources or reserves and for some of them, there is a gap between demand and supply as discussed in the following sections.

3.5.1 Cadmium (Cd)

This metal is used mainly in CdTe solar cells. Cadmium is a key metal in developing this kind of thin film solar cells. Results indicate that the need for this metal in some roadmaps will be more than available resources. All the investigated scenarios predict high need to cadmium in short and long term roadmaps. In this study a recycling rate of 20 % was considered for recycling process and as presented in figure 3.8, accumulation of cadmium in 2050 can't support our future demands of this metal. At current state, a low precentage (1-2 %) of this metal is used in CdTe industries so that other industries like Ni-Cd batteries are main consumer of this metal. After Ni-Cd batteries, Cd is mainly used in other applications like plating, coating and pigments. High deployment potential of solar PVs in IPCC-2050 roadmap (70 EJ/year) is the main reason for the lack of cadmium in 2050. Except IPPC-2050 other scenarios also will face with shortage of this metal. Based on USGS data, the average content of cadmium in zinc ores is 0.03%. Considering 230 million tons as global reserves of zinc, it is possible to evaluate global reserves of cadmium to be nearly 69000 tons.

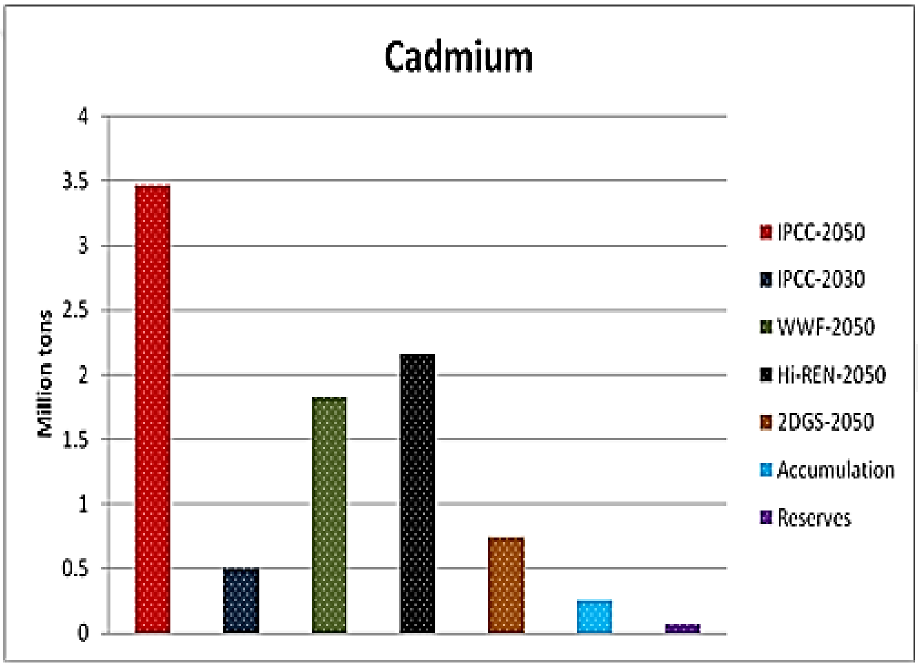


Figure 3.8 : Cadmium demand, available reserves and calculated accumulation in this study.

3.5.2 Cobalt (Co)

Cobalt is another resource which has a high potential for shortage in 2050. It is used in different renewable energy conversion technologies. In this study recycling rate related to cobalt was considered to be 50 %. Results indicate that demand for cobalt in IPCC-2050 roadmap will be around 59.4 million tons which is more than eight times of current reserves of cobalt and also this value is equal with 40% of global resources of cobalt. Demand for cobalt in other scenarios including WWF-2050, IPCC-2030, 2DS-2050 and HiREN-2050 is 14.6, 49.5, 12.6 and 10.8 million tons which are more that current reserves of cobalt. Accumulation of cobalt in 2050 will be around 4.3 million tons that can't support all the demands of renewable energy conversion technologies based on these scenarios. One important parameter affecting on the shortage of cobalt in 2050 is the low production rate of this metal based on historical data. Figure 3.9 shows that there is a huge gap between supply and demand. In other words while there is a huge resources of cobalt, reserves are not considerable. To overcome this problem, it is required to improve the mining and extraction techniques of cobalt in order to increase the value of reserves of this metal for satisfying future demands.

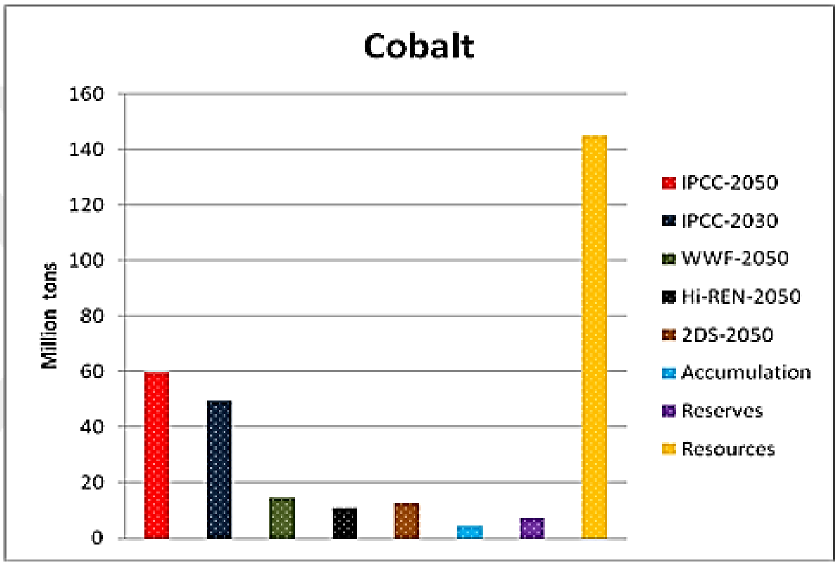


Figure 3.9 : Demand, available reserves, resources and calculated accumulation for cobalt.

3.5.3 Indium (In)

Indium is another key metal used in special type of solar cells. Calculations show a huge demand for indium in 2050 while the resources of indium are not enough. In other words in the case of indium we will face with a lack of resources and situation of this metal will be critical in 2050. Demand for indium in 2050 based on IPCC-2050 scenario is about 300000 tons while global reserves and resources of indium are 12400 and 95000 tons respectively [124]. Due to low recycling rate of indium (≈ 1 %) the accumulation for this metal in 2050 won't cover all the demand of indium. Results indicate that even in 2013 it is possible to face with problem in terms of availability of indium because of the consumption of this metal in other sectors like flat panel displays, solders, batteries and etc. Share of different sectors in indium consumption is presented in figure 3.10. As it is presented in figure 3.10, flat panel displays are the main consumer of indium with a consumption of more than 50 % of produced indium. In 2011 the share of PVs in global consumption of indium was 8 % which is expected to grow in next decades due to fast deployment of this technology.

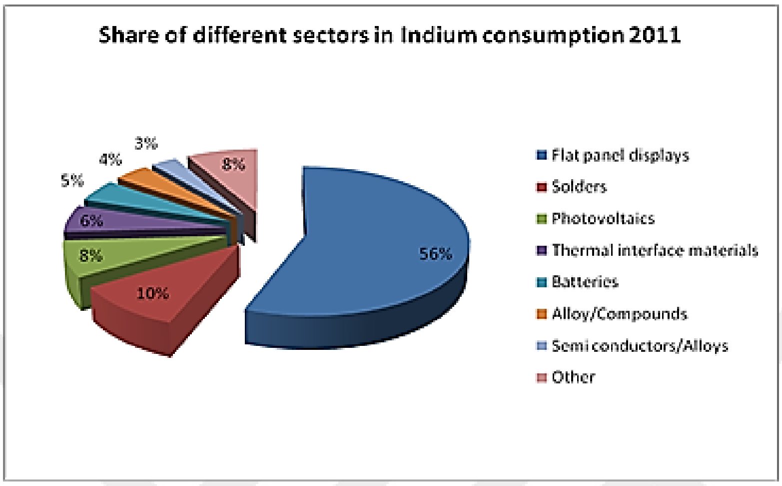


Figure 3.10 : Indium consumption by different sectors in 2011 [125].

Required Indium based on different renewable energy scenarios are presented in Figure 3.11. Based on this figure, the lack of indium resources will be an obstacle against reaching the 100 % renewable energy planet as it is predicted in other studies [37, 39].

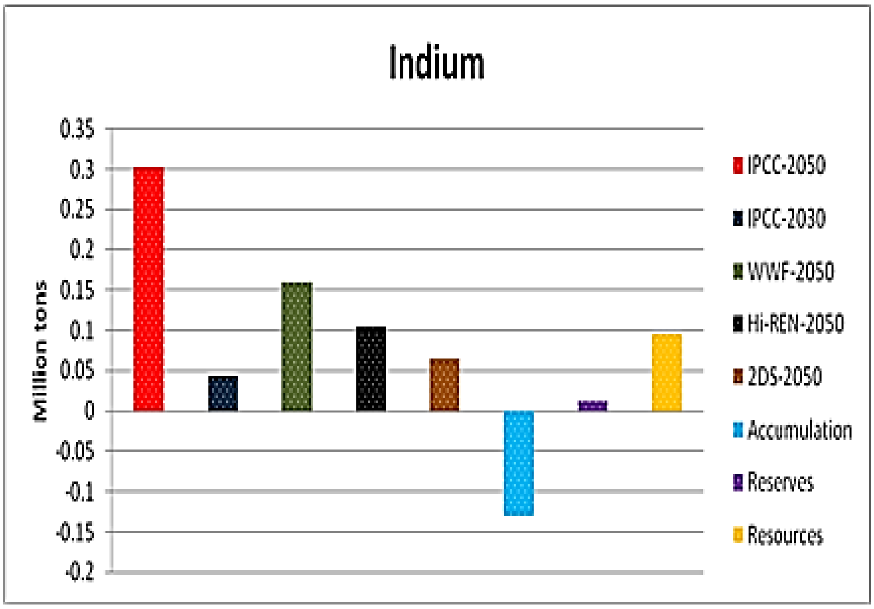


Figure 3.11 : Intensity of demand, accumulation, reserves and resources of indium.

3.5.4 Rare earth metals; neodymium (Nd) and dysprosium (Dy)

Rare earth metals (REMs) are 17 elements including 15 elements of Lanthanoids plus Sc and Y. Some of the rare earth metals like Nd and Dy are important due to their wide application in permanent magnets used in wind turbines. Rare earth metals are normally found together in geological deposits that leads to high cost for extracting individual metals. Because of fast growth of wind turbines, average growth for demand of REMs is about 5.3 % in some scenarios [126]. In 2010 about 20 % of demand for REMs was related to Nd consumption in magnets while this value for Dy was around 1 %. Also in 2013 about 89 % of produced neodymium was used in permanent magnet of as is presented in figure 3.12.

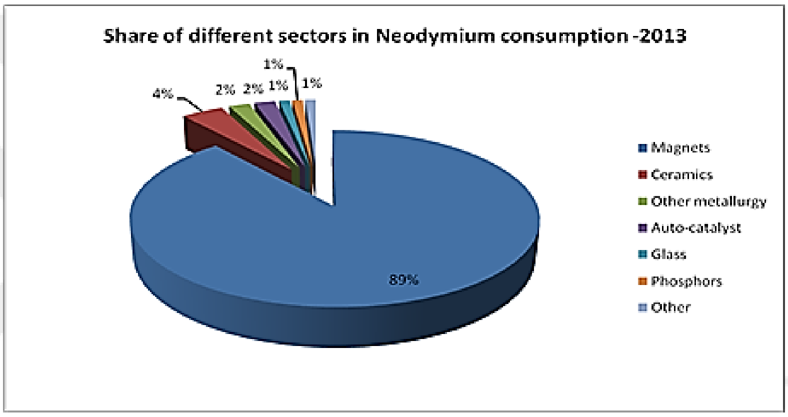


Figure 3.12 : Share of different sectors in neodymium consumption in 2013.

Different scenarios predict different demand growth for neodymium and dysprosium. In the case of dysprosium, based on different scenarios [126] demand for this metal will reach to 2500 tons considering 5% annual growth. However, in some other scenarios, consumption of dysprosium will reach to 25000 tons in 2035. Considering mentioned rage of growth for dysprosium, demand for this metal in 2050 will be between 5000 and 40000 tons per year while global production of dysprosium is around 1600 tons in 2015. In other words, demand for dysprosium in 2035 must be 25 times of current production rate of dysprosium in some scenarios. In the case of neodymium, results of this study indicates a high demand for this metal in 2030 or 2050. Neodymium is considered as a key metal in developing wind turbines in 2050 and 2030. The results indicate that in scenarios with higher levels of energies, the shortage in reserves of neodymium will happen considering a renewable energy world in 2050 or even in 2030. Accumulation for neodymium in 2050 was a negative value indicating the high consumption rate (5.6%), low production rate and low recycling rate (1%). In other words while the resources of REMs is huge and abundant, there is a huge gap between supply and demand in case of neodymium. Figure 3.13 indicates the demand for neodymium in different scenarios and also the calculated accumulation for this metal in 2050. Reserves of rare earth ores is about 130 million tons which is equal with 109.2 million tons of REMs. Between 16-20 % of extracted REMs is formed by neodymium thus global reserves of neodymium will be between 17 and 21 million tons (≈19 million tons).

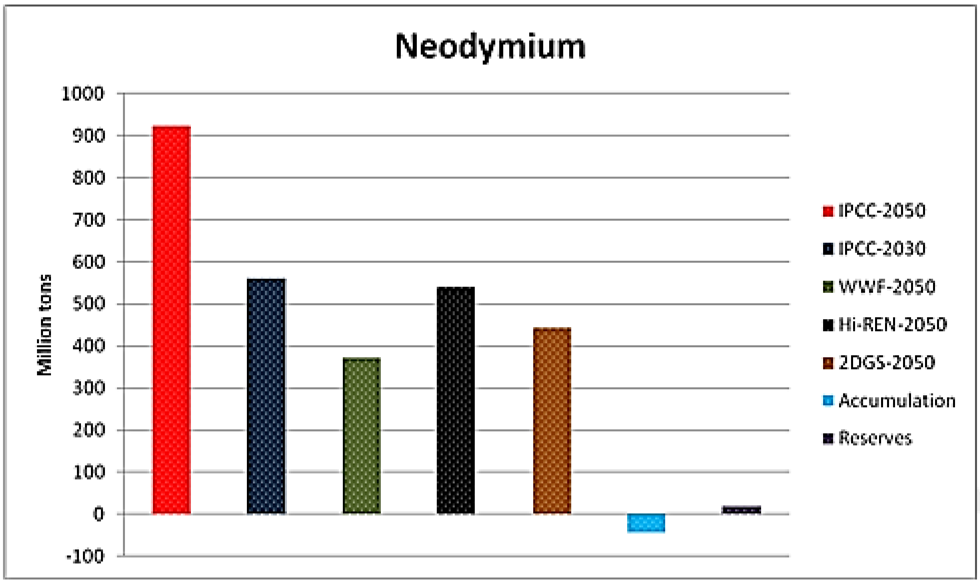


Figure 3.13 : Demand, accumulation and reserves of neodymium

As it is presented in figure 3.13, demand for neodymium in IPCC-2050 roadmap will reach to 900 million tons. Demand for this metal in all the scenarios are more than the current recognized reserves. Improving the extraction and separation techniques is the key solution for overcoming the supply- demand gap.

3.5.5 Other sensetive resources

Except resources mentioned in the previous section which are critical in terms of their availability for a renewable energy world in 2050, there are some other metals that their consumption in 2050 is considerable. In other words, there are enough resources for these metals but share of their consumption in 2050 by the renewable energy conversion technologies is considerable. These metals have a lower degree of criticality in compared to some metals described in section 3.5 but growth of their consumption by other industries can cause a shortage in future.

3.5.5.1 Tellurium

Tellurium is the fundamental metal used in CdTe solar cells. Demand for this metal in 2050 based on IPCC-2050 scenario will be around 5 % of the current recognized reserves. In another study by Elshkaki ane Graedel [36], this metal is considered as one of the metal with potential of shortage. In this study [36] Tellurium is considered as the most critical resource of PVs in terms of resource availability and production capacity. Based on results of current study, the location of tellurium on the y=x line is close to the neighborhood of critical region. This means that there might be an availability issue fo Te in the future.

3.5.5.2 Tantalum

Tantalum is another key metal which is used widely in different renewable energy technologies like solar PVs. Based on the current results the demand for this metal will be considerable in IPCC-2050 roadmap due to high share of solar PVs in this roadmap. Calculations show that more than 12200 tons of tantalum will be consumed in 2050 by renewable energy conversion technologies which it is about 12 % of current recognized global resources of tantalum. Tantalum has a low recycling rate (≈ 1 %) and thus this metal has an availability problem in the future.

3.6 Conclusions

In this study availability of 35 resources including metals and water for reaching a renewable energy world in 2030 and 2050 was investigated. Different roadmaps such as IPCC, WWF, IEA-HiREN and IEA-2DS were employed in the assessment of the renewable energy technologies. However there are some earlier studies related to availability of metals in renewable energy technologies, the current study can be considered as comprehensive study in terms of both number of investigated metals and long term scenarios that it covers. Results of this study indicate that key metals in important renewable conversion technologies like solar PVs and wind turbines will face with shortage. In other words, we will face with lack of indium and cadmium which are the key metals used in different solar PVs like CdTe and CIS solar cells. In case of indium, there are not sufficient resources for supporting the demands of a renewable energy planet while in case of cadmium the reserves can't undergo our demands in 2030 or 2050. Cobalt is also another metal which is used in different renewable energy technologies. Based on data presented by USGS, there are enough resources of cobalt while the reserves are not huge. In other words to overcome the supply problems of Cobalt, it is necessary to fill available gap between our demand and supply through improving our mining and extraction technologies. Neodymium and dysprosium are other key metals which are used in permanent magnets of wind turbines. While there are sufficient resources for these metals in the crust of earth, the reserves are limited so that current production rate won't be able to satisfy our demand in 2030 and 2050. Based on results of this study considering the resources limitations about solar PVs (CdTe and CIS) and wind turbines, reaching a 100% renewable energy world won't be possible in near (2030) and also short term (2050) roadmaps. In other words, it is necessary to improve recycling rate and also to substitute these metals with other synthetic materials (i.e., Polyethylene terephthalate) to overcome resource limitation of mentioned metals. Solar PVs and wind turbines (off-shore) have a considerable share in the renewable energy scenarios and their share in long term roadmaps reaches to around 20%. Thus reaching to a 100 % renewable energy plant has serious obstacles so that overcoming the limitations of mentioned key metals is the first step toward a renewable energy world. Ta and Te are two other metals that may face availability problem because of low recycling rate and production rate of these metals, respectively. Production rate of Te is low while the demand for this metal is increasing due to the fast deployment of CdTe solar cells. Ta has low recycling rate while the consumption of this metals is increasing because of the application of this metals in other technologies like fuel cell vehicles. Based on results of current study, there is suffiecient amount of the water for the renewable energy technologies in 2030 and 2050. Results of this study indicate that there is sufficient resources and reserves for other investigated metals like Cu, Ni and etc.

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PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

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