EVALUATION OF SOLAR SLUDGE DRYING ALTERNATIVES ON COSTS AND AREA REQUIREMENTS

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EVALUATION OF SOLAR SLUDGE DRYING ALTERNATIVES ON COSTS AND AREA REQUIREMENTS

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all the material and results that are not original to this work.

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ABSTRACT

EVALUATION OF SOLAR SLUDGE DRYING ALTERNATIVES ON COSTS AND AREA REQUIREMENTS

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There are basically two common sludge drying methods, thermal drying and solar drying. While thermal drying requires high amount of energy, solar drying cannot typically attain the 90 % DS requirement. The literature studies emphasize the benefits of solar drying used as GSD (greenhouse solar dryer) to reduce energy requirement but these dryers cannot achieve 90 % DSC without any auxiliary heat. Therefore, use of solar panels as auxiliary heat source was evaluated in this study. To calculate how much energy and area is required in the drying system, an optimization problem was written. Area limitation was used as a constraint in this optimization problem. The results showed while DS_m ratio is 70 % DS, the total cost was minimum. On average, 58 % of the total cost and 38 % of total required area consisted of GSD cost and the rest was solar panel cost. The area is important parameter to reach high DSC. WWTPs (waste water treatment plants) whose sludge flow rate is higher than 5 ton/hr are not suitable for GSD due to area limitation. Although GSD with solar panels has high investment cost, it is more economical than thermal dryers for long term energy requirement. To conclude, this study demonstrates that solar panels can be used as auxiliary heat source for a GSD instead of a thermal dryer if enough area, solar radiation, ventilation and mixing of sludge is provided.

Keywords: Area Constraint, Cost Optimization, Greenhouse Solar Dryer, Solar Panel, Sludge Drying, Thermal Dryer.

ÖZ

ÇAMURUN GÜNEŞLE KURUTMA TEKNİKLERİNİN MALİYET VE ALAN İHTİYACI ÜZERİNDEN DEĞERLENDİRİLMESİ

Kurt, Mayis
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Temel olarak iki tip çamur kurutma yöntemi vardır, termal kurutma ve güneşle kurutma. Termal kurutma yüksek miktarda enerji gerektirirken, güneşle kurutma genellikle % 90 kuruluğa erişemez. Literatür çalışmaları enerji maliyetlerini azaltmak için güneşle kurutma sistemlerinin sera tipi kurutucular olarak kurutulmasının önemini vurgulamaktadırlar, ancak bu kurutucular herhangi bir yardımcı ısı olmadan % 90 kuruluğa erişememektedirler. Bu nedenle, yardımcı ısı kaynağı olarak güneş panelleri kullanımı bu çalışmada değerlendirilmiştir. Kurutma sistemindeki gerekli alan ve enerji miktarını hesaplamak için bir optimizasyon problemi yazıldı. Bu optimizasyon probleminde, alan sınırlaması bir kısıt olarak kullanılmıştır. Sonuçlara göre DS_m oranı % 70 iken toplam maliyet en düşük çıkmaktadır. Toplam maliyetin ortalama % 58'ini sera tipi kurutucu oluştururken gerekli alanın ortalama % 38'ini kaplamaktadır, geri kalan kısım ise güneş paneline aittir. Alan daha fazla kuruluk oranına ulaşmak için önemli bir parametredir. Alan kısıtlamasından dolayı çamur akış hızı 5 ton/s 'ten daha büyük olan AATler için sera tipi kurutucular uygun değildir. Güneş panelleri ile birlikte kullanılan

sera tipi kurutucuların yatırım maliyeti yüksek olmasına rağmen, uzun vadede enerji ihtiyacından kaynaklı termal kurutmadan daha ekonomiktir. Sonuç olarak, bu çalışma gösteriyor ki sera tipi kurutucular yeterli alan, güneş radyasyonu, havalandırma ve karıştırma değerleri sağlandığı takdirde güneş panelleri ek ısı kaynağı olarak değerlendirildiğinde termal kurutucu yerine kullanılabilmektedir.

Anahtar Kelimeler: Alan Kısıtlaması, Çamur Kurutma, Güneş Paneli, Maliyet Optimizasyonu, Sera Tipi Güneş Kurutucu, Termal Kurutma.

To My Beloved Family

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LIST OF ABBREVIATIONS

$	Dolar
€	Euro
^0C	Celcius degree
AK	Mediterranean Region
Cd	Cadmium
CHP	Combined Heat Power
CO_2	Carbon Dioxide
Cr	Crom
Cu	Copper
DS	Dry Solid
DSC	Dry solid content
DS_i	Initial Dry Solid Content
DS_m	Intermediate Dry Solid Content
DS_f	Final Dry Solid Content
EGE	Aegean Region
EMRA	Energy Market Regulatory Authority
EPA	Environmental Protection Agency
Eq	Equation
EU	European Union

GSD	Greenhouse Solar Dryer
GÜN	Southeast Anatolian Region
hr	Hour
ha	Hectare
İÇ	Central Anatolian Region
J	Joule
K	Potassium
KAR	Black Sea Region
kg	Kilogram
kJ	Kilojoule
kW	Kilowatt
kWh	Kilowatt-hour
MAR	Marmara Region
m^2	Square Meter
m^3	Cubic Meter
Mg	Mega-gram
MJ	Mega-Joule
mm	Mili meter
N	Nitrogen
n.d.	No date
Ni	Nickel

P	Phosphorus
Pb	Lead
PV	photovoltaic devices
SS	Sewage sludge
t	ton
TL	Turkish Lira
U.S.	United States
UK	United Kindom
VOC	Volatile Organic Compound
W	Watt
WWTP	Wastewater Treatment Plant
yr	Year
Zn	Zinc

NOMENCLATURE

ρ	The air density	kg/m^3
A_{GSD}	Area of greenhouse solar dryer	m^2
$A_{WWTP,i}$	The area of treatment plant i	m2
$C_{CGSD,i}$	The unit construction cost of the greenhouse solar dyer i	TL/m2
c_{ea}	Unit average energy cost	TL/kWh
c_{en}	Cost of electricity at night time	TL/kWh
c_{er}	Cost of electricity supplied from renewable solar energy	TL/kWh
C_{inv}	The investment cost	TL
C_{off}	The pay-off time	yr
$c_{p,f}$	Specific heat of fixed solids	kJ/ kg-^{o}C
$c_{p,vo}$	Specific heat of volatile solids	kJ/ kg-^{o}C
$c_{p,w}$	The specific heat of water	kJ/ kg-^{o}C
c_{SP}	Unit cost of panel	TL/watt
c_{TL}	Unit cost of electricity	TL/kWh
DS_f	Final dry solid content	%
DS_i	Initial dry solid content	%
DS_m	Intermediate dry solid content	%
$E_{d.i}$	The total energy requirement to dry sludge in plant i	kJ/hr
$E_{d\_D,i}$	The energy requirement during day time to heat sludge	kJ/hr

$E_{d\_N,i}$	The energy requirement during night time to heat sludge	kJ/hr
$E_{Dd,i}$	Daily required energy	kJ
$E_{f.i}$	Energy requirement to reach fixed sludge to a temperature of Tf in plant i	kJ/hr
e_{GSD}	Unit energy consumption for ventilation and mixing	kwh/ton water
$e_{V,i}$	The evaporation rate at location i	kg water/m^2.h
$E_{vo,i}$	Energy requirement to heat up the volatiles in sludge to Tf	kJ/hr
$E_{w,eva,D}$	Required energy to evaporated remain water for reaching 90% DS during day time	kJ/hr
$E_{w,eva,N}$	Required energy to evaporated remain water for reaching 90% DS during night time	kJ/hr
$E_{w,evap,i}$	Energy required to evaporate water from sludge in plant i	kJ/hr
$E_{w,i}$	Energy requirement to heat up the water in sludge to Tf in the sludge in plant i	kJ/hr
h_f	Enthalpy of liquid water at specified condition,	kJ/ kg
h_v	Enthalpy of vapor at specified condition	kJ/ kg
$m_{e,i}$	The amount of water that should be evaporated to reach the desired sludge dry matter content at WWTP i	kg/hr
$m_{e,i}$	Is the mass of evaporated water from sludge at WWTP (ton water),	(ton water),
$m_{f,i}$	Mass flow of the fixed sludge which is assumed 25% of dry sludge in plant i	kg/hr

$m_{s,i}$	Mass of wet sludge at plant i	kg/hr
$m_{vo,i}$	Mass flow of the volatile sludge which is assumed 75% of dry sludge	kg/hr
$m_{w,evap,i}$	Mass flow of the evaporated water in the sludge	kg/hr
$m_{w,i}$	Initial mass flow of the water in the sludge	kg/hr
n	The efficiency factor	%
P_n	The required power at night time	kW
P_t	The overall power capacity of panels	kW
$P_{WWTP,i}$	The required power for WWTP	kW
Q_m	The air mixing rate	m^3 air/m^2area.h
Q_v	The ventilation rate	m/h
$R_{o,i}$	The solar radiation at location i	W/m^2
T	Time	
T_f	Final temperature	^oC
T_i	Initial temperature	^oC
$t_{N,i}$	Night time duration hours at location i	hr
$T_{o,i}$	The outdoor air temperature at location i	^oC
$t_{s,i}$	Sunshine duration hours at location i	hr
V_E	Required energy for ventilation to evaporate 1 ton water from sludge	kJ/ton-water
$Z_{C\_GSD,i}$	Construction cost of GSD i	TL

$Z_{C\_SP\_D,i}$	Construction cost of solar panel for day time	TL
$Z_{C\_SP\_N,i}$	Construction cost of solar panel for night time	TL
Z_{COST}	Total cost construction solar panel and solar drying bed	TL
$Z_{D,i}$	The capital cost of thermal dryer unit	TL
$Z_{GSD,i}$	The total construction and operation cost of greenhouse solar drying unit	TL
$Z_{O,i}$	The operating cost of thermal dryer unit based on the energy requirement	TL
$Z_{O\_GSD,i}$	The operation cost of GSD	TL
$Z_{SP,i}$	The construction cost of solar panel	TL
$Z_{TD,i}$	The total cost of thermal dryer	TL

CHAPTER 1

INTRODUCTION

The ever increasing water use due to population growth causes the increment of wastewater. This situation results in construction of new wastewater treatment plants (WWTP) as well as the need to increase the capacities of current WWTPs. As the amount of wastewater increases, so is the amount of sludge generated during wastewater treatment. As WWTPs operate on different systems, the quantity and quality of sludge produce changes. Depending on treatment facilities, sewage sludge could be solid, semi-solid or liquid (EPA, 2002). This varying moisture composition leads to the need for better sludge management or handling enforcement. Legislations restrict the dry matter content of sludge in Turkey for different management options. For example, “Regulation Regarding Landfilling of Wastes” (2010) restricts sludge disposal into landfills for dry solid (DS) contents of less than 50 %. “Regulation on the use of Domestic and Urban Wastewater Treatment Sludges on Land” (2010) states that a WWTP serving a population equivalent equal or higher than one million has to dry its waste sludge at least to 90% DS. These regulations enforce WWTP operators to dry their waste sludge.

Dewatering, drying and thickening are three techniques to remove water from sludge. These techniques can remove water by up to 32 %, 6 % and 63 %, respectively (Flaga,2007). Drying has a number of advantages compared to dewatering and thickening. It can remove more water than dewatering and thickening, which results in volume of sludge to be minimal. Reducing sludge volume decreases transportation cost. Also, dried sludge with thermal drying does not need any stabilization or pathogen removal. Dry sludge can be stored easily and safely (Flaga, 2007). Moreover, dry sludge is preferable than the wet one because it can be used as an alternative fuel source in a combustion facility or as a soil conditioner in agriculture

(Stasta, 2005; Flaga, 1995). To reach all of these benefits, the most commonly used drying technique is thermal drying. A thermal dryer is a machine, which works with heat exchange principle. It uses a fossil fuel to heat the drying surface or drying air (Flaga, 1995). Emissions and high-energy cost are the disadvantages of a thermal dryer. To reduce the high cost, integration of co-generation systems, use of waste heat or addition of solar energy can be used. In this study solar energy drying option is evaluated for sludge drying.

Today solar radiation is the most common renewable energy source. Greenhouse solar drying is an approach to use solar energy to dry sludge. Greenhouse solar dryer is constructed as tunnel type greenhouse, sludge in dryer is mixing and air in to dryer tunnel is ventilating. Greenhouse solar dryer is cheaper, its operation is easy, and it does not need skilled labor when compared to thermal dryers (Ritterbusch et al., 2012). Nevertheless, this system cannot reach 90 % DS at any time, any region. Therefore, this system should be supported with additional energy. Use of solar panels can be an alternative to get additional energy to reach 90 % DS or to minimize required sludge drying area. Fruit and vegetable drying generally uses solar panels to reach high drying ratio within a short time (Sandler, 2006). However, there is lack of studies about sludge drying with solar panels and/or combination of solar panels with greenhouse solar drying.

This study evaluates the use of solar power to dry sludge to 90 % DS based on capital and operational costs. The study includes comparisons of costs associated with both conventional and co-generation aided thermal drying as well. 37 WWTPs are considered in this study. These plants are chosen based the incoming wastewater flow rates. The first 11 WWTPs in Turkey with the highest flow rates were studied. Analysis was performed based on costs and areas required for sludge drying to reach the target dryness values. Cost functions and an optimization model were utilized to calculate costs and area requirements. Optimal costs for greenhouse solar dryers supported with solar panels were determined using EXCEL Solver.

CHAPTER 2

LITRETURE SURVEY

2.1. Wastewater Sludge and Production Rate

Sewage sludge could be a solid, semi-solid, or liquid residue based on the sludge treatment method applied. The amount of sludge produced during wastewater treatment depends on several factors such as climate, culture, consumption habits, treatment technologies etc. (EPA, 2002). Sludge production in WWTPs generally ranges from 35 to 85 g DS per population equivalent per day (gTS $PE^{-1}d^{-1}$) (Tchobanoglous et al., 2003).

High urbanization rate, developing industry and population growth have increased sewage sludge production. European Commission indicates that while annual sludge production in Europe was 5.5 million tone of dry matter in 1992; it increased to nearly 9 million tones by the end of 2005(European Commision, 2012).With the increment of urbanization of Turkey, sewage systems and number of WWTPs are increasing, too. ENVEST report stated that total sludge amount in Turkey is 1,075,000 ton dry sludge/year in 2008 (ENVEST, 2010). Figure 2.1 shows expected sludge amount for Turkey which was estimated to be 3,100 ton dry solids per day for 2013 (ENVEST, 2010).

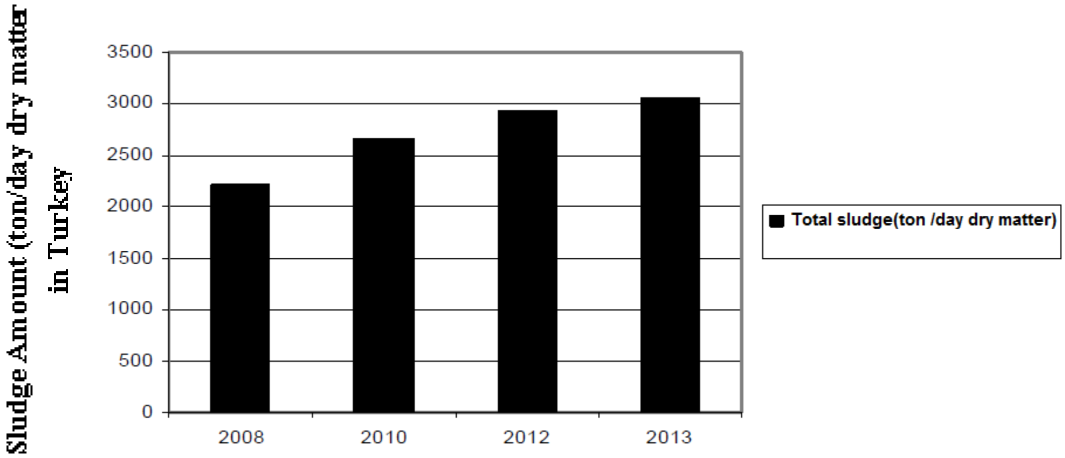


Figure 2.1 Total sludge amount predictions (ton/ day) (ENVEST, 2010)

2.2. Composition of Wastewater Sludge

Raw sludge obtained from wastewater treatment consists of 95 to 99% water. Remaining part is the solid sludge with different compositions depending on the type and characteristics of influent, treatment technology applied and operational conditions (Houdková et al., 2008). Typical raw sludge consists of 60.27% carbon, 6.51% hydrogen, 24.89% oxygen, 8.35% nitrogen, and 0% sulphur (Houdková et al., 2008). After digestion, the values change to 62.70% carbon, 8.27% hydrogen, 19.45% oxygen, 7.38% nitrogen, and 2.22% sulphur, respectively (Houdková et. al., 2008). The contents of dried sludge from municipal WWTPs are similar to the composition of brown coal, which has 21 MJ/kg of calorific value (Stasta etal., 2006).Sludge also includes phosphorus and potassium compounds. Typical values for stabilized wastewater sludge are 3.3% nitrogen, 2.3% phosphorus, and 0.3% potassium (Tchobanoglous et al., 2003; Harrington, 2013).Although these values are lower compared to fertilizers for typical agricultural use (5% nitrogen, 10% phosphorus, and 10% potassium), sludge provides sufficient nutrients for good plant growth (Metcalf, 2003). In order to benefit from the solid particles of sludge the obstacle of high water content should be reduced.

2.3. Beneficial Use and Disposal Methods of Wastewater Sludge

Produced sewage sludge proceeding wastewater treatment process could either be disposed or used for its high nutrient values. The most common disposal methods are incineration, land application and landfilling, while sludge can also be used as a fertilizer in agricultural purposes or as an alternative fuel in cement factories (Gray, 2010). Today, 53% of sewage sludge produced in Europe is reused in agricultural applications, while 21% of it is incinerated (Escalaet al., 2013).

There are three common beneficial use of the sludge; incineration, alternative fuel for combustion process such as in cement production and usage as fertilizer in agriculture. The disposal method on the other hand is landfilling. The water content of sludge impacts the cost of transport, level of effort for disposal or the cost of incineration (Keller et al., 2005)

2.3.1. Sludge Incineration

Incineration of sludge is accomplished by the combustion of sludge at high temperatures in enclosed vessels, which enables conversion of sludge into mainly carbon dioxide, water and ash (McFarland, 2000). The major advantages of incineration are high volume reduction thereby reduction in the amount that needs to be disposed, destruction of pathogens and toxic compounds, and energy recovery potential. Incineration of sludge is usually performed on dewatered sludge. Volatile matter and moisture content of the sludge determines the auxiliary fuel requirement and needs to be optimized before incineration (Metcalf, 2003;McFarland, 2000).

Although incineration has its benefits, it requires large capital investment, highly skill labor and has high operating cost. Also products formed during the process such as flue gases, ashes and wastewater arising due to stack gas treatment system, could be harmful to environment and might be classified as hazardous wastes. Despite these disadvantages, countries with high population prefer to handle their sludge via incineration. In countries like Japan, Netherlands, Germany, Slovenia, Canada and USA, incineration is an important part of sludge disposal (Table 2.1).However, incineration in Turkey is not as popular as in the mentioned countries. There first large scale incineration plant was IZAYDAS which has been handling hazardous wastes, industrial sludge sand certain other wastes from industries. This plant is still properly operating in Izmit/Kocaeli in Marmara Region. However, it does not accept municipal sewage sludge (UNHSP, 2008). PETKIM- İzmir (2003), Tüpraş- İzmit (2006) and İSTAÇ (construction continues) are the relatively newer incineration plants in Turkey.

Table 2.1 Incineration application in different countries (UNHSP, 2008)

Country	**Incinerated Sludge %**
Japan (Fujiki)	> 70%
Netherlands (Kreunen)	58%
Germany (Schulte)	34%
Slovenia (Grilc)	50%
Canada	33.3%
USA	15%

2.3.2. Sludge use as an alternative fuel source

In Europe, more than 64% of facilities use waste materials as alternative fuel source. Figure 2.2 shows the percentages of the use of waste material in some European countries. The figure illustrates that Netherlands is the country that uses sewage sludge in the highest quantity as an alternative fuel (42%).

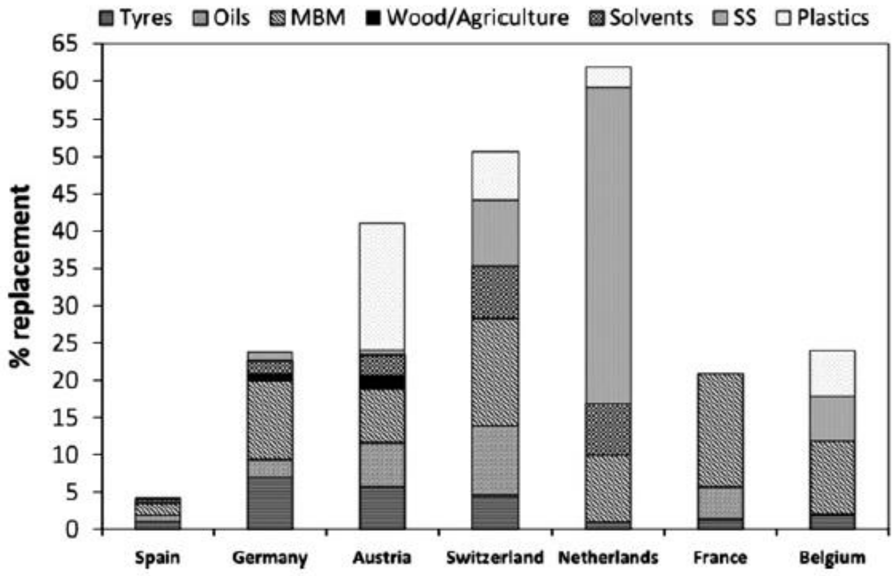


Figure 2.2 Ratio of replacement regarding the type of alternative fuel by country (Uson et al., 2013) (SS: sewage sludge)

According to Madlool et al.(2011) and Mokrzycki et al.(2003), alternative fuel sources should have heat values higher than 14 MJ/kg and have lesser than 20% water content. Although targeted heat value can be met, high moisture content of sludge constitutes a burden for its use as a fuel. While wet sludge can be used in direct combustion units, heat loss is 2257 kJ/kg-water and there is high ash content which reduces the energy that can be obtained(Uson etal., 2013).To prevent this energy loss, sewage sludge can be dried using the waste heat from cement kilns. If there is not such an option, drying is suggested before using sewage sludge as an alternative fuel in a cement factory (Uson et al., 2013).

Sewage sludge can be used as an alternative fuel for a number of industries including cement factories (Uson et al., 2013). Cement factories consume 10-15% of the total industrial energy in worldwide and produce 6% of the total global CO_2 emission. EU countries encourage the use of alternative fuel sources to reduce fossil fuel consumption and greenhouse gas emissions (Uson etal., 2013; Valderrama et al., 2013).

In Turkey, Nuh Cement Factory, Akçansa Cement Factory, Aslan Cement Factory are an example using sludge as an alternative fuel source. The factory is collecting wet sewage sludge from WWTPs close by, and drying the sludge with the waste heat of the plant until it reaches to 90% DS. After that, dried product is used as an alternative fuel source in the cement factory. They utilize 250 ton sludge/day which satisfies 3% of the energy requirement of cement production (Personal communication with plant operators, 2012).

2.3.3. Land Application of Sludge as Fertilizer on Agriculture Lands

U.S. Environmental Protection Agency (EPA) Land Application of Sewage Sludge Guide (1994) defines land application as “the spreading, spraying, injection, or incorporation of sewage sludge, including a material derived from sewage sludge (e.g., compost and pelletized sewage sludge), onto or below the surface of the land to take advantage of the soil enhancing qualities of the sewage sludge.” Sewage sludge is applied for enrichment of soil structure or supplying nutrients to soil where crops or vegetation are grown. Sewage sludge is generally used as a fertilizer due to its enriched nutrient contents (EPA, 1994). Main fertilizer values (N, P, and K) and concentration of trace metals in sludge determines whether sludge could be used for agriculture. Heavy metals (Zn, Cu, Pb, Ni, Hg, Cr and Cd)in the sludge area concern because excessive amount of these metals may accumulate and adversely impact plant yields or quality of food or grain produced (Sommers, 1977; Schowanek, et al., 2004).

Using sewage sludge for agricultural purpose is not only environmentally acceptable but also cost effective. Agricultural land application is cheaper than other alternative methods of sewage sludge use and disposal. This method does not require to purchase or rent places to dispose sludge. Additionally, sludge supplies nutrients for crop production with lower costs than for commercial fertilizers (EPA, 1995). However, sewage sludge application on agricultural lands can be potentially risky to human health because sewage sludge can result in exposure of environmental and ecological receptors (i.e. animals, plants, and organisms) to contamination due to accumulation of high levels of metals, trace elements, PCB’s, dioxins, steroids, pharmaceuticals, pathogens, bacteria, viruses, and disease vectors (National Research Council, 2002; Aktar et al., 2008; Reilly, 2001).

Despite of the potential disadvantages, sewage sludge is currently used in agriculture for its beneficial purposes. 2 to70 tons of dry weight sludge/ha is applied in agricultural lands every year, which have moderate water content (EPA, 1995).60%, 54%, 50%, 44%, and 26% of the sludge produced in France, Denmark, Spain, UK and USA, respectively, are used for agricultural purposes (Werthera et al., 1999). Table 2.2shows the estimated percentages of agricultural areas required to handle all sludge produced in different countries through application on soil.

Table 2.2. Estimated percentage of agricultural area required to apply countries' wastewater sludge (UNHSP, 2008)

Country	Estimated sludge production (Mg)	Estimated sludge production Mg/ha of agricultural Area	% of agricultural area req'd to apply sludge at 5 dry Mg/ha
Germany	1,783,323	0.105	2.1%
Netherlands	356,816	0.186	3.7%
Japan	2,757,856	0.588	11.8%
U.S.	6,457,264	0.0156	0.3%

2.3.4. Sludge Landfilling

Landfilling is a disposal method where sludge is deposited in a specific area of land or in an excavated area. It is a permanent storage method for waste, residuals and sewage sludge. Sludge can be stored either by itself (monofill) or with solid waste (co-disposal). Although there is no specific technical constraint on sludge disposal in a landfill, municipal landfills do not accept unlimited amount of sewage sludge due to regulations (EPA, 1993; European Commission, 2001). Following the enactment of the Directive on the landfilling of waste (1999/31/EEC), most European countries reduced disposing biodegradable sludge in landfills and prohibited the landfilling of both liquid wastes and untreated wastes (EPA, 1999). In Netherlands, ashes and residuals from sludge can be landfilled if organic matter is less than 10% of the dry matter content. In France, the 1992 Waste Act restricts the landfilling of sewage sludge from 2002 onwards: from this date, landfilling is limited to waste that cannot be recovered at reasonable cost. In Sweden, no organic waste including sewage sludge is accepted in landfills (European Commission, 2010). In Turkey, according to “Regulation Regarding the Landfilling of Wastes (2010)”, a landfill can accept sludge above 50% dry matter content. Figure 2.3 shows sludge handling and disposal methods adopted in Europe in 2005. Although regulations prohibit or restrict landfill or disposal, sludge can be landfilled when composition is not adequate for use in land application or recycling and processing (i.e. incineration) (European Commission, 2013).

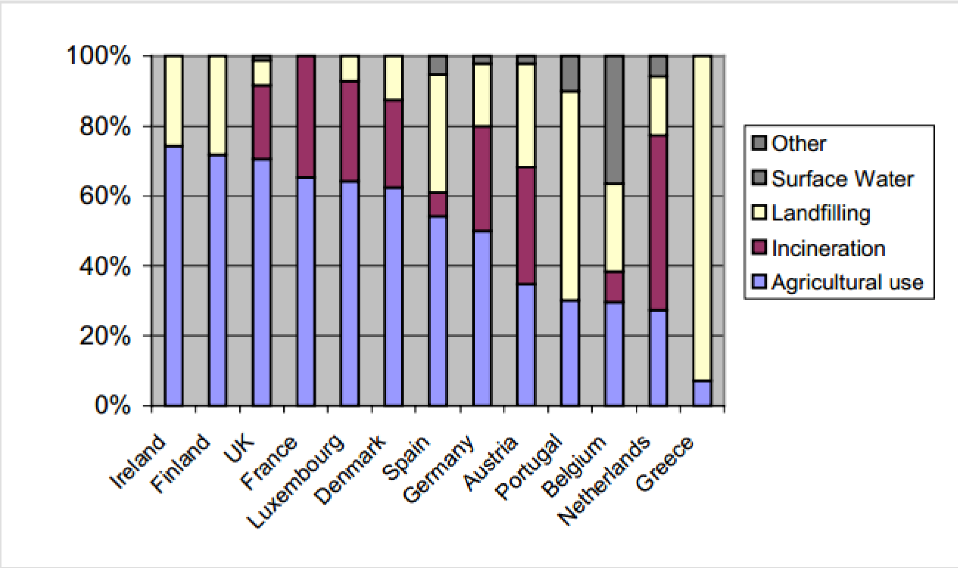


Figure 2.3 Estimated destinations of sludge in the member states by the year 2005 (European Commission, 2001b)

Landfilling operations may cause air, water and soil contamination, therefore they should be controlled. The decomposition of organic matter in sewage sludge that is landfilled has a risk to produce greenhouse gases which are 50 to 60% CH_4 and 40 to 50% CO_2. Additionally, dust emission, noise and odor during handling of waste and VOC emission will affect the air quality. Leachate occurs in a landfill system, which also can potentially harm both soil and water. It includes several compounds such as ions (Ca^{2+}, K^+, Na^+, NH_4^+, CO_3^{2-}, SO_4^{2-}, Cl^-), heavy metals, organic compounds (chlorinated organic, phenol, benzene, pesticides) and microorganisms. If leachate is not treated or controlled, it can contaminate soil and water easily (European Commission, 2013).

2.4. Water Removal from Wastewater Sludge

Slurry, semi-solid or solid sludge produced following wastewater treatment should be disposed. Section 2.3 explains some disposal and beneficial use of sewage sludge. Sewage sludge should contain a minimum amount of dry matter in order to be used as auxiliary fuel for incineration and as an alternative fuel source in cement factories to enhance combustion efficiency, provide safety, and reduce emissions during combustion (Chai, 2007). Also high dry matter content is essential to meet the criteria in the regulations relevant to sewage sludge landfilling and reduce transportation cost of sludge to agricultural lands (Chai, 2007).For example, decreasing the moisture content of sludge from 75 % to 20-30%resultedin a decrease in transportation cost from 222,500 €/yr to 79,500€/yr (Bux et al., 2003). Additionally, energy consumption decreased by 50-75% by decreasing the water content of the sludge (IETS Annex X, 2008).Thereby, water removal is critical. There are three major water removal techniques from sludge; thickening, dewatering and drying.

2.4.1. Sludge Thickening

Thickening is a process, which reduces the water content in sewage sludge; thereby not only solid content of sludge increases but also overall sludge volume decreases. Thickening process can enrich 0.8% of DS content of sludge to 4%. This process is desirable because it reduces both the capital and operational cost of subsequent sludge-processing steps. Even though sludge thickening process leads to high volume reduction ratio (almost 80%), physical characteristic of sludge is still fluid. Co-settling thickening, gravity thickening, flotation thickening, centrifugal thickening, gravity-belt thickening, rotary-drum thickening are some thickening processes (Metcalf, 2003; McFarland, 2000).

2.4.2. Sludge Dewatering

Dewatering is the water removal technique to reduce the water content and total volume of sludge. Typically dewatering comes after thickening and after dewatering, sludge is no longer a fluid. Dewatered sludge can be carried with a belt conveyer easily or transported by trucks. Since after dewatering sludge becomes a solid, the transportation and sludge handling costs are reduced, incineration efficiency is increased, and leachate production potential during landfilling is reduced. Typical dewatering processes are centrifugation and belt filter press (Metcalf, 2003; McFarland, 2000).

Centrifugation uses the centrifugal force developed by a rotating cylindrical drum or bowl to achieve liquid-solids separation. The centrifuge is essentially a high-energy settling unit. By this technique, it is possible to reach 25-35% dry solid content (DSC) (McFarland, 2000; Chen etal., 2012).

Belt Filter Press dewaters sludge by forcing the water out from sludge under squeezing shear forces. Product sludge achieves 15-25% DS content while raw sludge solid concentration is 2-5% DS (Metcalf, 2003; Chen etal., 2012).

2.4.3. Sludge Drying

Drying is the process, which can remove high amount of water from sludge. While thickening and dewatering can remove7% and 35% of the total amount of water, respectively, drying can remove up to 62% additional water content after applying these two systems (Flaga, 2007). Sludge drying is an energy intensive process. This system not only reduces volume but also stabilizes sewage sludge. Transportation, storage, packaging and retailing are easy and cost efficient for dried sludge. Drying increases calorific value of sludge. Thereby, sludge can be incinerated without auxiliary fuel. Moreover, its potential as an alternative fuel in cement factories improves. Dried sludge is also beneficial for agricultural purposes. Drying makes sludge hygienic (without pathogenic organism), improves sludge structure and increases its market value (Flaga, 2007; Chen etal.,2012). A number of Turkish regulations require sludge drying. For example, “Regulation Regarding the Landfilling of Wastes” (2010), restricts the disposal of sludge that has less than 50 % DS into landfills. “Regulation on the use of Domestic and Urban Wastewater Treatment Sludges on Land (2010)”states that a WWTP serving a population equivalent higher than one million should be dried its waste sludge at least to 90%

DS. All of these can make drying an important step in wastewater treatment plants. Figure 2.4 shows a general mass balance for water content in sludge in a typical treatment scheme.

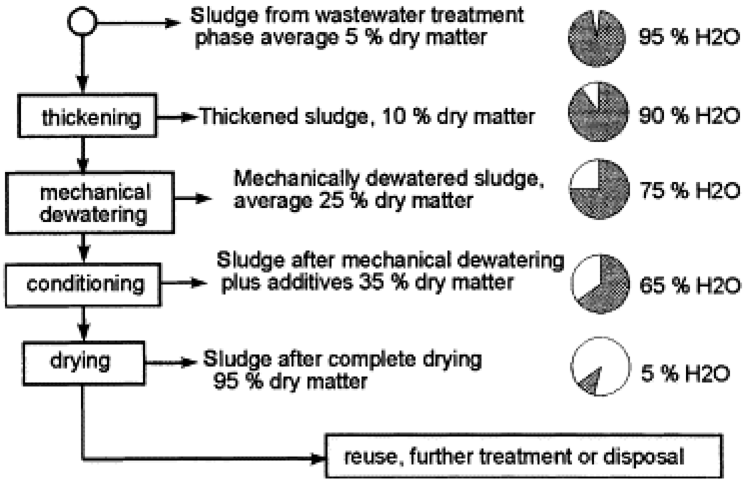


Figure 2.4 Material balance: water–solid mass (Werthera et al., 1999)

2.5. Sludge Drying Techniques and Methods

As mentioned in the previous sections, drying is the most important water removal technique to get rid of high amount of water to from sludge to reach high DSC (dry solid content). There are two commonly used drying techniques, thermal drying and solar (sun) drying to obtain higher than 50% dryness. Thermal drying is classified with regard to the method of heat transfer as direct (convection), indirect or contact (conduction), radiant (radiation) and dielectric or microwave (radio frequency) drying, and can provide 90% dryness. Solar drying has been traditionally applied in the form of sun drying beds. Recently sun drying beds are converted into greenhouse solar dryers by covering the dryer, mixing the sludge and ventilating air in the dryers. In this study, solar drying in the form of greenhouse solar dryer (GSD) will be considered.

2.5.1. Thermal Drying

Thermal drying is a continuous operation which reduces the water content of sludge by heating it for short periods. Dried product not only reaches granular formation with 92 – 95% DS but also gets stabilized. Thermal drying is a complicated process with contemporary heat and mass transfer attended by physicochemical transformations. Drying occurs as a result of vaporization of liquid by supplying heat to wet feedstock (Mujumdar et al., 2007). Evaporation rate of water from sludge does not have a constant value (Figure 2.5). It changes during drying process because bonding of water to sludge is not one kind. There are four different types of binding which classifies the type of water in sludge into four; free water (constant rate period), interstitial water (first falling rate), surface water (second falling rate) and bound water (Figure 2.5) (Bennamoun, 2012; Sahni et al., 2012; Deng, et al., 2009; McCormick, 1988).

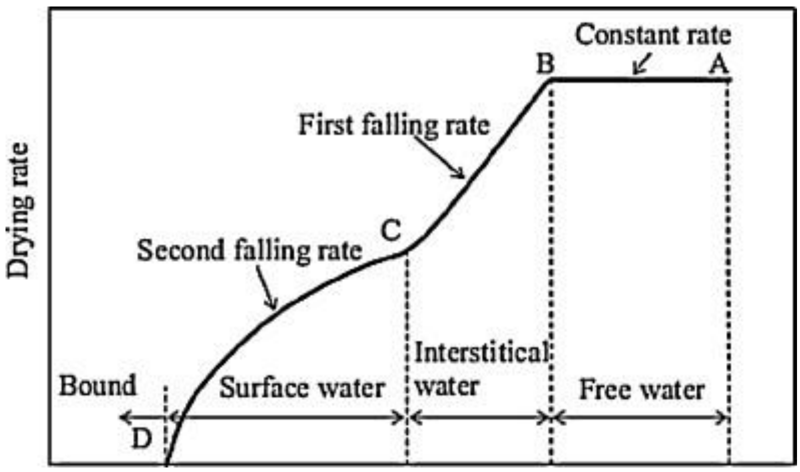


Figure 2.5 Moisture content versus drying rate (Bennamoun, 2012)

Free water from sludge is unbound water, which can be removed by thickening (gravity settling) (Vesilind, 1993). *Interstitial water* is held in sludge by adhesion and cohesion forces that can be readily removed from sludge by mechanical dewatering without using chemicals. Centrifuges can be suitable to remove water in this phase (Bennamoun, 2012). *Surface water*, which is physically half-bound water, is bound inside the flecks of sludge. *Bound water* can exist as: physical, chemical and biological forms (Flaga, 2007). Physical form – in colloids form- is bound by the surface tension present on the border of phases. Chemical form - in intercellular form, is a part of the crystal lattice of molecules of the constant phase of sludge. Biological form-intracellular form- is a part of the cells of living organisms present in sludge, bound by molecular forces to the solids in sludge (Flaga, 2007). Although colloidal and intercellular forms of water can be eliminated by dewatering process or adding polyelectrolytes, removal of the surface and bound water is only possible by breaking sludge particle walls with either heating, freezing or by electro induced forces. That means that removing biologically bound water of sludge is only possible by adding extra energy to the system such as thermal energy (Flaga, 2007).

2.5.1.1. Types of Thermal Drying:

A thermal dryer is classified with regard to the method of heat transfer: direct (convection), indirect or contact (conduction), radiant (radiation) and dielectric or microwave (radio frequency) drying. *Direct dryers* use sensible heat, hot air or gas, which contacts with the soil sludge. To increase the energy efficiency of a direct dryer, some of the heat in hot exhaust gases is recovered and recycled back through the combustion chamber. Also, depending on the degree of sludge drying, dried sludge is recirculated as necessary. Rotary drum, moving belt and fluidized bed are some examples of direct dryers (Sahni et al., 2012; Fonda et al.,2009; Flaga, 2007).*Indirect dryers* transmit heat energy to the sludge by conduction, as heated surfaces pass through or come into contact with sludge. Different types of gases (steam, hot gas) or liquids (hot water, oil and glycol solution such as propylene glycol) are used to heat the contact surface. Paddle dryers, thin- film dryers, and rotary-disc dryers are typical indirect dryers (Fonda et al., 2009; Uhl et al., 1962). Compared to direct driers, indirect dryers reduce odor, dust, and air pollution. Direct dryers release high dust and volatile compounds. According to Flaga (2007), indirect dryers are less economical than direct dryers. They have usually long time of sludge retention and also limited efficiency of drying. As dried sludge concentration can achieve up to 85% solids content with indirect processes, it is possible to dry it to higher than 90% solids content with direct drying processes (Fernandes, 2007).Several energy resources could be used for indirect driers while direct driers typically use light fuel oil or natural gas. There are other drying methods, which are relatively rare in use. *Radiant dryers* use radiation from a hot gas or a surface as the primary source of heat transfer. *Dielectric dryers* employ electromagnetic fields to transfer energy and achieve drying (Root, 1983; Malhotra et al., 1992; Stasta et al., 2006).

2.5.1.2. Energy Requirements of Thermal Drying

A thermal dryer requires high amount of energy to perform. Typically, required energy is 2627 kJ/kg-biosolid or 2595kJ /kg-water (0.72 kW/kg-water) (Fonda et al., 2009; Lowe, 1995). Natural gas, electric power, biogas (methane), waste heat, recovered heat (CHP system) and solar energy are the potential energy sources that can be utilized by a thermal dryer. *Natural gas* is widely used in drying furnaces. It is a widely available and a relatively cheap fossil fuel (Fonda et al., 2009). *Electric power* provides a reliable source of energy as well. *Biogas* can be produced from landfills or digesters by using anaerobic process. It is also a sufficient fuel source to reduce costs in comparison to other fuels (Havelsky, 1999; Fonda et al., 2009).*Waste heat* can be obtained from heat producing processes such as incineration and cement production. The hot flue gas from the process is used to produce steam in a special boiler. This steam can be used to get electricity or heat oil which is used in the indirect drier to heat surface. (URL 1, personal communication). Hence, use of waste heat reduces external energy need. *Recovered heat (CHP system)* is obtained with the heat exchanger that enables the utilization of exhaust heat from combustion products and cylinder cooling of the drive combustion engine. The cogeneration system consists of a gas engine, a generator for power production and an absorption refrigeration system that produces chilled water or hot water according to demands. The waste heat of jacket water and exhaust gas of the gas engine is used as the heat resource of the absorption refrigeration system. Therefore, this system has high energy production efficiency compared to other energy production systems (Havelsky, 1999; Sun, 2007). *Solar energy* is the most economical energy source. It also has the lowest impact on environment. However, the ability of solar energy to dry sludge depends on geography and season (Fonda et al., 2009). Figure 2.6 shows the energy sources used for sludge drying in EU and USA. Solar energy and co-generation systems are the most preferable applications to dry sludge.

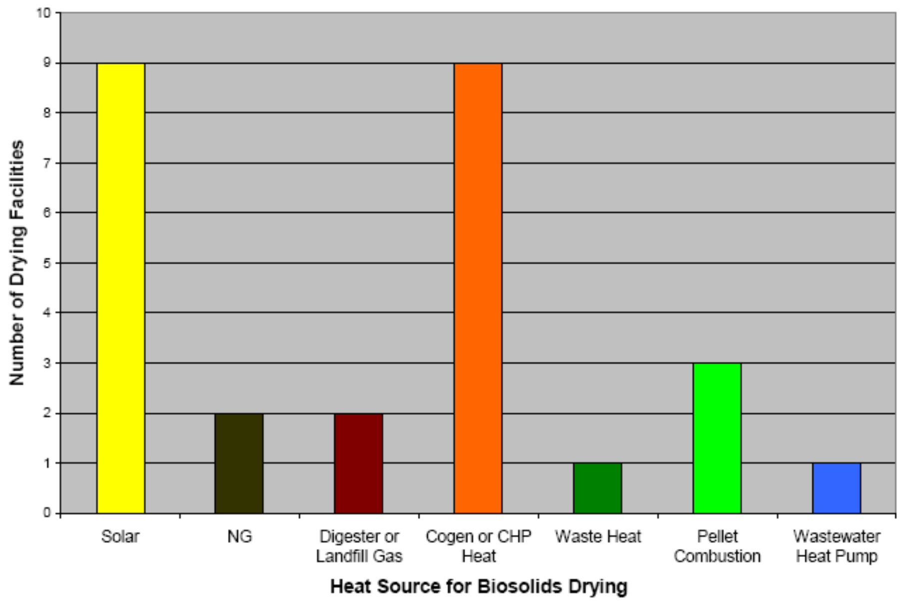


Figure 2.6 Biosolids (sludge) drying methods used in dryer facilities currently operating in Europe and the USA (Fonda et al., 2009)

2.5.1.3. Typical complications of sludge drying in a thermal dryer

There are two basic problems while using a thermal dryer. The first one is the sticky phase of the sludge and the second one is the risks of ignition and burning of sludge during the process. While sludge is drying, sludge changes its slurry form to a paste form, which is similar to sticky rubber. This phase is called as the sticky phase. Sticky phase causes a problem in the drying unit because sticky sludge clings to the walls/surfaces of the dryer, and reduces drying performance of the dryer. Sticky phase occurs in municipal sludge between 45 % and 65% of DS content. Overcoming the sticky phase problem is achieved through mixing the dewatered sludge (20- 35% DS) with dried sludge (90-95% DS). Therefore, dry matter content of sludge increases up to 65-75% DS at the inlet. Increasing DS content of sludge improves granule formation which is particularly important for further usage and utilization of the sludge (Flaga, 2007; Malhotra, 1989; Mollekopf et al., 1982).

There are risks of ignition and burning of sludge during thermal drying due to VOCs in the sludge. New drying systems are improved to operate at lower drying temperatures by recovering waste heat from low grade heat material. Using low heat reduces dust formation during the process and reduces the risk of ignition as well.

This application not only lowers the energy usage but also increases the overall safety of the dryer. Rarely, using low temperature might result in a final product DS below 90 %.

2.5.2. Solar Drying

Solar drying is one of the oldest drying techniques in which solar radiation is used, i.e. drying under direct sunlight to preserve food or non-food products since ancient times. Solar drying does not require man produced energy, uses renewable energy and applicable in any part of the world. Nevertheless, in order to increase the efficiency of sludge drying using solar radiation, proper innovation or application is needed. Owing to costly, limited, and non-environmentally friendly fossil fuels, solar drying is becoming a popular option to replace the mechanical thermal dryers (Hii et al., 2012).

2.5.2.1. Conventional types of Solar Dryer Systems

Solar energy has been used for sludge dewatering purposes. Paved solar bed and sand drying beds are examples of traditional solar driers. A *Paved solar bed* is an asphalt or concrete paved area, constructed as sand drains. If sludge-settling properties are good, it is possible to remove 20-30% of water from sludge. Drying period depends on climatic conditions. For example, in an arid region, a sludge bed with 30 cm thickness can reach up to 40 to 50 % DS in 30 to 40 days (EPA, 1987). A *Sand drying bed* is a drying bed supported with drainage channels. Sludge is laid in 200 to 300 mm thickness and allowed to dry. Sand drying beds can easily dry sludge beyond 25-40 % DS and can even dry the sludge up to 60 % dry solid content given adequate detention time. Drying beds are generally used for small and medium sized community or industrial wastewater treatment plants. Although the method is simple and requires minimal operation attention, it has disadvantages due to large area requirement and dependence on climatic conditions. Climatic conditions and low drainage rate may also cause odor and low pathogen removal (Metcalf, 2003; Al-Muzaini, 2003; Ögleni et al., 2010).

Pathogen removal efficiency being low in conventional drying beds may cause a problem because it limits the sludge use (Ritterbusch et.al., 2012). In U.S., Class A sludge is the desirable level for applying the sludge on lawns, home gardens and can be either sold or given away in bags or transported within other containers (EPA, 1997). In order to reach the A grade, E.*coli*, fecal coliform and *Salmonella* should be lower than 100MPN/per gram (dry weight), 1000 MPN/per gram (dry weight), and not detectable, respectively (EPA, 1997). Although sludge can reach class B by some stabilization techniques such as anaerobic digestion, aerobic digestion, and lime stabilization without using a drying unit, it needs to be dried in order to reach class A quality. Pathogenic microorganisms can be significantly removed during hot and dry periods. Using modified sand bed areas, drying under the sun for a long time or heating the bed underneath are some solutions to obtain better pathogen removal in a shorter time.

In a case study in Jordan, conventional non-modified sand drying beds and modified sand drying beds were compared. Drying beds consisted of 0.6 m thick layer of gravel and sand. Sludge was applied on those beds with 25 cm of thickness. Modified bed included galvanized pipes, which carried hot water to dry sludge. The system had temperature sensors to measure temperature at different locations and sludge depths. Solar collector cells (Figure2.7) of a total surface area of 20 m^2were used to heat water, which flowed through the network of pipes under the sludge layer. The sludge absorbed the heat provided by hot water circulation, and cooled water circulated back to a storage tank to be reheated again (Radaideh et al., 2011).

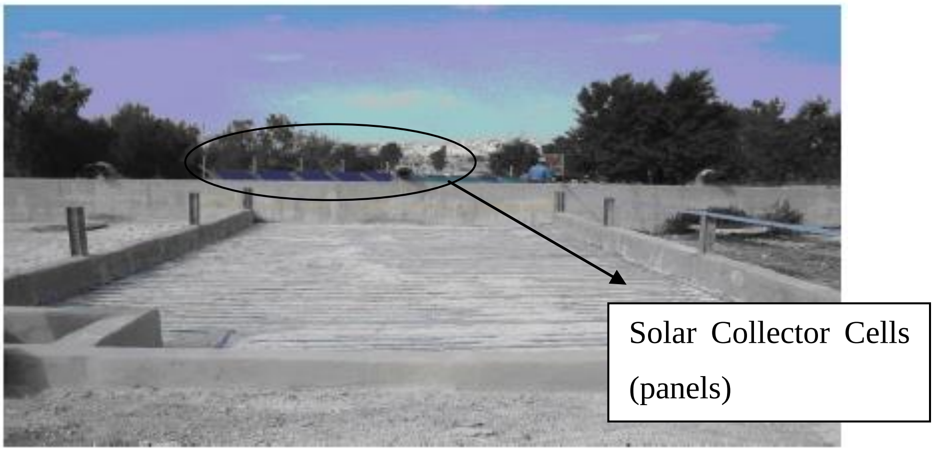


Figure 2.7 The modified bed with the galvanized pipe network (Radaideh et al., 2011)

The water content of the sludge decreased from 96.5% to 32.94% within 18 days in conventional drying beds in Jordan. When the modified drying bed was used, the drying time reduced by 60% to reach the same dryness. Compared to conventional drying beds, the water content of sludge was dropped by 7.9% in the modified beds in the same duration. Additionally, when temperature in the conventional drying beds was increased, 100% removal of some pathogenic species was achieved. Other contaminants and pathogens could be reduced by 99% in the modified drying beds (Radaideh et al., 2011).

2.5.2.2. Greenhouse Solar Dryer

A greenhouse solar sludge drying plant can be constructed as a tunnel type greenhouse. It can entirely be enclosed with thick transparent polycarbonate sheets to provide light transmittance (some covered with glass) as illustrated in Figure 2.8. The indoor aeration is achieved with a ventilator so that the humidity indoors is removed and kept stable. Sludge is periodically mixed so that it can be dried homogenously. A study showed that in Greece, 8 kg of dewatered sludge was placed in a greenhouse solar dryer in 20-25 cm depth. Sludge moisture content decreased from 85% to 6% within 7-15 days in summer and down to 10% within 9-33 days in autumn. If the same system was supported with auxiliary heat, drying process took 1-9 days in winter (Bennamoun, 2012).

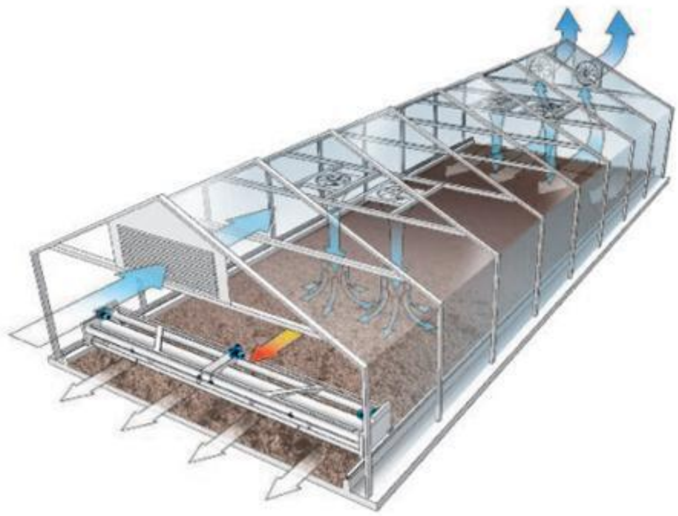


Figure 2.8 A schema of a greenhouse solar drying system (Huber, 2007)

Greenhouse solar dryers are environmentally friendly and they have very low CO_2 emissions when they are compared with thermal systems, because they do not use fossil fuel or use little fossil fuel for ventilation and mixing purposes. In addition, solar drying systems are cheaper because they can operate at low temperatures (10-40^oC) and they are easy to maintain. Labor is required for loading wet sludge and placing the dried sludge in greenhouse solar dryers. Use of a simple machine for transport purposes, no requirement for continuous operation and educated personnel for emergency cases are the advantages of solar greenhouse drying systems. This system is also advantageous for pathogen removal compared to conventional drying beds (Bux et al., 2003).

Technologies, such as thermal dryers, can dry the material more rapidly, but at the cost of additional energy (Mangat et al., 2009). Advantages of solar drying are low energy requirement and production of sludge containing low total mass of biosolids due to avoidance of bulking agents (such as in composting or chemicals as in lime stabilization.). Depending upon the particular system installed, the solids with initial DS concentration of 2 to 35% can be dried up to 90% DS which enables this technology to be attractive for small to medium sized plants in moderate climates and also for larger sized plants in warm climates (Seginer et al., 2005).

A study performed by Salihoğlu et al., (2007) in Bursa, compared open drying beds with covered drying beds in terms of pathogen removal. Open drying beds provided 60% moisture content in 55 days while covered drying beds achieved 20% moisture content during the same time. The study of Salihoğlu (2007) focused on pathogen removal. He concluded that a greater pathogen reduction was achieved with the covered sludge drying system compared to the open system in summer time. Prior to drying, the coliform content of mechanically dewatered sludge was 10^7 CFU g^{-1}DS whereas at the end of 45 days in the covered solar drying area, the coliform content decreased to below 2×10^6 CFU g^{-1}DS (the limit for EPA's Class B pathogen requirement) in summer. However, to obtain the EPA's Class A pathogen requirement of 1000 CFU g^{-1}DS in a short period of time, limited amount of lime was added to the dewatered sludge prior to solar drying. The required coliform level was achieved in an average of 10 days in summer and in 20 days in winter. Use of a heating floor, solar water heater, infrared lamps, heat pumps or adding thermal energy storage systems could increase both drying performance and pathogen removal ratio (Salihoğlu et al.,2007; Bennamoun, 2012; Shanahan et al., 2010).

2.5.2.2.1. Facilities of Greenhouse Solar Dryer Application Examples in the World

There are many full-scale examples and studies about greenhouse solar driers in the world. By the end of 2003, there were 48 active solar drying plants in the world. 65% of these plants were in Germany, Switzerland, Austria, France, USA, Italy and Australia (Bux et al., 2003).

A study which evaluated25 treatment plants in Europe showed that evaporation rates during sludge drying ranged between0.6-1.0 ton/m^2. In cases where a heating system was incorporated, this value increased up to 3.5 ton/m^2. In the treatment plants that do not have any dewatering units, evaporation rate was also high, which was 2-3 ton/m^2, due to higher performance in drainage of free water in a drainage floor. In specific study areas in Germany, Switzerland and Austria, evaporation rates in dewatered sludge were measured as 0.5-1.1 ton evaporated water/m^2.yr. In a treatment plant in southern Germany, the dried matter content reached to 60-70%.

The required drying area was calculated as 0.8-1.2 m²/ton-wet-sludge per year for dewatered sludge that was dried without any back up heating. For sludge that was not dewatered, required area was calculated as 0.3-0.5 m²/ton-wet-sludge per year due to high evaporation rate (Bux et al., 2003).

De Mallorca (Spain) and Oldenburg (Germany) have the largest greenhouse solar dryers in the world. These plants are good references to estimate the drying performance of greenhouse solar dryers. Figure 2.9 illustrates the view of the sludge dryer of Palma de Mallorca area of which is 20,000 m^2. The area of Oldenburg plant is 6000 m^2 and can handle 40,000 tons of wet sludge totally originating from different WWTPs. While initial dryness (DS_i) is 15-30%, final dryness (DS_f) is achieved as 60-70% in the Oldenburg solar drying plant. The amount of dried sludge at this place is 6 times more than the unassisted solar drying units at the same climatic condition (Ritterbusch et al., 2012).

Figure 2.9A view of Palma de Mallorca greenhouse solar drying plant in Spain with 20 000 m² area, (Ritterbusch et al., 2012)

The study in Nicaragua by Scharenberg et al., (2010) showed that the sludge dryness of which is 28% could reach 70% DS in 3 weeks of drying. In the same study it was reported that sludge amount decreases to 4300 kg/m^2 per year at rainy season. If drying time is 30 days, 87% DS could be achieved. Furthermore, 20 kWh of energy is required for evaporation of one ton of water without a non-continuous ventilation system. This value is almost 800-1000kWh for thermal drying systems.

Unfortunately, the required ground area is quite large which is about 8000 m², or 0.4 m²/ton of filtered cake. This value increases to 1.2 m²/ton of filtered cake in middle Europe due to lower ambient temperatures. The capital cost of the system in Nicaragua is 690 €/yr dry ton of sludge. In addition, this drying plant is the largest greenhouse solar dryer in America as commissioned in 2010. Figure 2.10 and 2.11 are the views of afore mentioned sludge drying plants.

Figure 2.10 A view of the solar sludge drying plant in Managua/Nicaragua (Scharenberg et al., 2010)

Figure 2.11 Another view of the solar sludge drying plant in Managua/Nicaragua (Scharenberg et al., 2010)

An example greenhouse solar sludge dryer is at Fethiye wastewater treatment plant in Turkey (Figure 2.12). This system is designed to reach a final DSC of 50%.The area of the facility is 2000m^2. In summer time, sludge can dry up to 85% within 2-2.5 days. In wintertime, this duration increases to 3.5 days and final dry solid content achieved to 50 % DS (Personal communication with plant operators, April 2013).

Figure 2.12 Fethiye Waste Water Treatment Plant Greenhouse Solar Drying Unit (April, 2013)

2.5.2.2.2. Design Parameters of a Greenhouse Solar Dryer

Design parameters of a greenhouse solar dryer are evaporation rate, sludge production rate, and final dryness (Seginer et al., 2006;Segineretal., 2007). Drying in this system depends on mean ambient temperature, solar radiation, ventilation, mixing of sludge, and initial dryness of sludge, which are the parameters independent of the size of treatment plant. Mixing and ventilation are also significant to increase the evaporation rate. Mixing and ventilation can be applied in different ways. Figure 2.13, 2.14 and 2.15 show some examples of mixing and ventilation.

Figure 2.13 A greenhouse solar dryer system by Huber (URL 14)

Figure 2.14 Delivery of wet sludge, drying and loading of dried sludge in the solar drying plant of Palma de Mallorca (Ritterbusch et al., 2012)

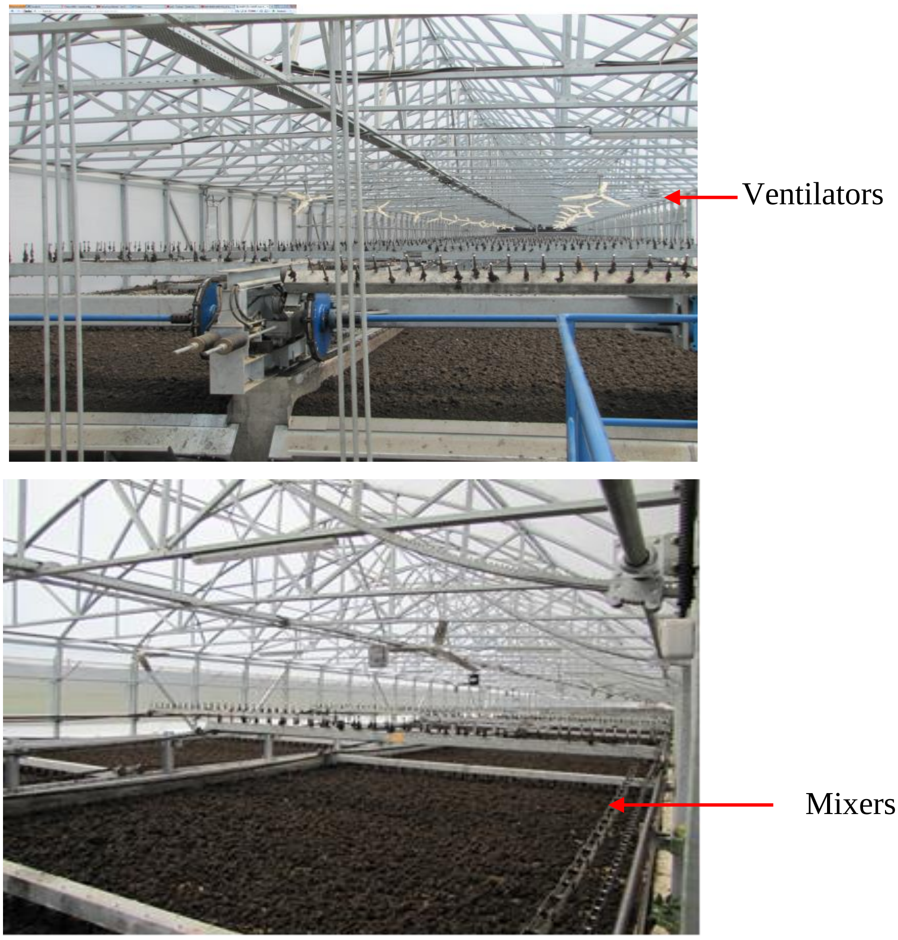


Figure 2.15 Fethiye Waste Water Treatment Plant- Solar Drying Unit

The energy required for operation of greenhouse solar drying systems is between 15 and 40kWh/ton of evaporated water when ventilation and sludge mixing devices are used. This value is 2 or 3 times less than the energy required for thermal drying. Additionally, less fuel and energy use decreases CO_2 emission. When CO_2 emissions for different drying systems are compared in Germany, 24 kg CO_2/ton of evaporated water was emitted in solar drying, while170 kg CO_2/ton of evaporated water was emitted in thermal drying. In other words, the CO_2 emission in solar drying plant is 15% lower than that of thermal drying plant (Ritterbusch et al., 2012).

2.5.2.2.3. Auxiliary Heat Use in Greenhouse Solar Driers

Auxiliary heat can be used in a greenhouse solar dryer in cold places to reach a high DSC or to decrease drying time. A greenhouse solar dryer can be supported with auxiliary heat by two ways. One way is that the base of the greenhouse dryer can be constructed as a gravel layer where heated water can be circulated easily. The other way is that hot air could be blown through the sludge surface (Weiss et al., n.d.). Figure 2.16 shows applications of these two ways of supplying auxiliary heat.

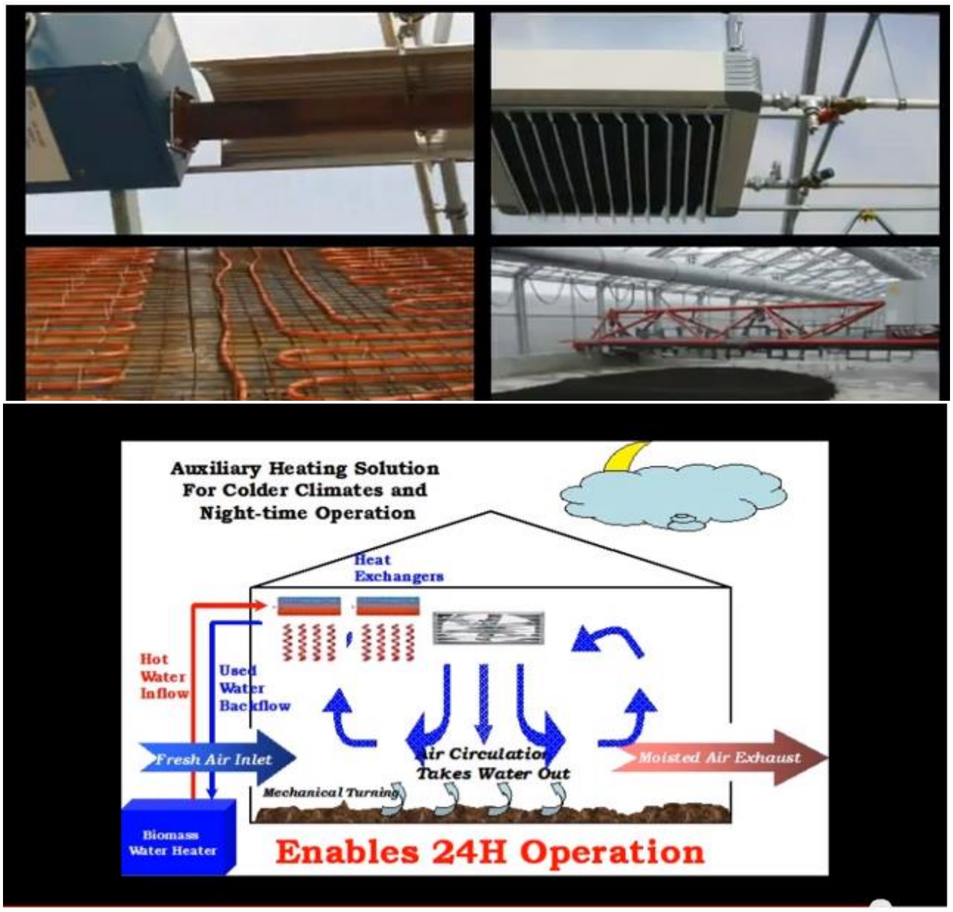


Figure 2.16 Auxiliary heating of greenhouse solar drying systems (snapshot from URL 2)

Auxiliary heat could be waste heat, heat obtained via renewable energy or conventional heat. Solar energy is one of the options. However, before deciding whether to use a solar panel, economic basis, effects on environment, and safety of solar panels should be considered. Although the initial investment cost of a solar panel is high when fuel costs are considered, solar energy is economical in long term. Other important aspects to consider are energy storage and converter systems (Duffie et al., 2013;Kalogirou, 2009). For instance, photovoltaic devices (PV), or cells, are used to convert solar radiation directly into electricity. They can be connected in both series and parallel to produce larger voltage currents. Energy production of PV systems depends on sunlight. They can produce any scale of energy required. Moreover, PV systems have a long life. They can also be used either independently or in conjunction with other electrical power sources (Lysen, 2013).Therefore, PV system is a good option to be used as an auxiliary source. Table 2.3 shows an example where thermal and solar drying costs are compared. For drying of the same amount of sludge, a solar dryer has cheaper investment and operation costs compared to thermal drying.

Table 2.3 Costs for solar drying of 25 ton/day of sludge from the feasibility report of Antalya-OSB (URL 3)

	Solar drying	Thermal drying
Investment Cost (TL)	2,500,000	5,000,000
Operation Cost (TL/month)	29,000	120,000
Energy expense(TL/month)	6,500	80,000
Maintenance and Personal expense (TL/month)	4,000	10,000
Sludge removal expense (TL/month)	18,500	30,000
Sludge Amount(ton/month)	750	750
Operation cost (TL/ton)	39	160

Use of solar panels to provide auxiliary energy reduces drying time and increases evaporation rate. Mathioudakis et al. (2009) used a solar panel to heat water to improve drying. In this system heated water was pumped and cycled through ground surface where sludge was dried. Following the enhancement of drying with this heating method, sludge with 15% initial dryness could be dried up to 90% dryness in winter within 9-33 days. This value in summer time was 94% dryness, obtained in 7-12 days. Moreover, pathogen removal increased to 99%. Another study in Poland

(Krawczyk et al., 2011) reported that an evaporation rate of 8.12 kg water/m^2 per day could be obtained just using solar energy without auxiliary heating. As an auxiliary heat source was added to this system via infrared lamps, drying rate increased to 11.11 kg water/m^2 per day. When heat was given from under the floor, drying rate improved to11.71 kg water/m^2 per day.

Another benefit of supplying additional heat is the decline in the area used for drying. When solar drying systems are combined with systems that use waste heat, required area for sludge drying decreases by 3 to 5 times. Also, the calorific value of final dried biosolids is high and the sludge is suitable for agricultural use (Ritterbusch et al., 2012).

CHAPTER 3

METHODOLOGY

The purpose of this study is to investigate the use of solar power to dry sludge to 90% DS on cost basis. For this option both grid-on and grid-off systems are considered. In the grid-on system a portion of the energy produced via solar panels is transferred to the electricity network to compensate for the energy required during night time. In a grid-off system there is no energy transfer to the electricity network. Analyses are based on capital operating and maintaining costs for drying for different conditions. In this study, a greenhouse solar dryer is supported by solar panels in order to reach 90% dry sludge. In this system solar panels are used as grid-on only. Associated costs are determined based on a linear optimization model solved by Excel Solver. Moreover, comparisons are made with respect to costs of sludge drying using thermal dryers with and without co-generation. These costs are obtained from a project (TUBİTAK-KAMAG, 2013). Thermal drying is the traditional approach used to dry sludge to 90% DS in a short time. Details regarding the assumptions used and cost functions are given below. Evaluations are performed on 37 selected biological wastewater treatment plants.

3.1. Study Area

According to TUBITAK KAMAG108G167 Project (TUBİTAK-KAMAG, 2013), there are 191 biological WWTPs in Turkey. In that project, overall costs of sludge drying using thermal dryer, greenhouse solar dryer, covered and open sludge dryer beds were evaluated and compared. Best drying methods were determined for each of 191 WWTPs through cost-based optimization. Figure 3.1 shows the optimal drying methods suggested for different WWTPs (TUBİTAK-KAMAG, 2013).The results of the optimization study indicated that 37 WWTPs with higher flow rates could use thermal drying. These 37 WWTPs were ranked at top based on their sludge production rates. The top 11 ones produced between 5,659.27 kg to 1,128.88 kg of dried sludge/hr. For the following 21 WWTPs in rank, sludge production rates ranged from 845.55 kg to 98.33 kg dried sludge/hr. In this study these 37 WWTPs for which thermal drying was suggested were considered (Figure 3.1).

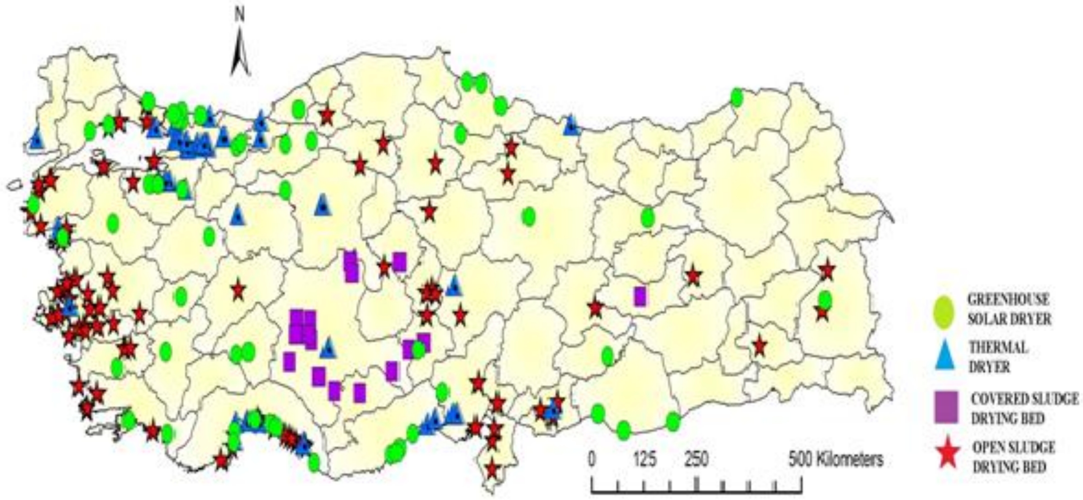


Figure 3.1 191WWTP distribution in Turkey (blue triangles show the 37 WWTPs considered in the study) (TUBİTAK-KAMAG, 2013)

The regional distribution of the 37 WWTPs considered in this study is as follows: 9 WWTPs in the Mediterranean, 21 WWTPs in the Marmara Region, 4 WWTPs in the Central Anatolia, 1 in the Aegean, 1 in the Blacksea, and 1 in the Southeast Anatolian Regions. The names of the WWTPs will not be provided due to confidentiality. Rather a naming convention is used such that an abbreviation indicating the region is combined with a number indicating a specific WWTP in the given region. The abbreviations of AK, MAR, İÇ, EGE, KAR, and GÜN, refer to the Mediterranean, Marmara, Central Anatolia, Aegean, Black Sea, and Southeast Anatolian Regions, respectively. The initial dry solid content of the produced sludge in 37 WWTPs ranged between 30 %-13 % DS with the exception of 2% DS in the MAR-15.The sludge production rates in 37 WWTPs are given in Figure 3.2.

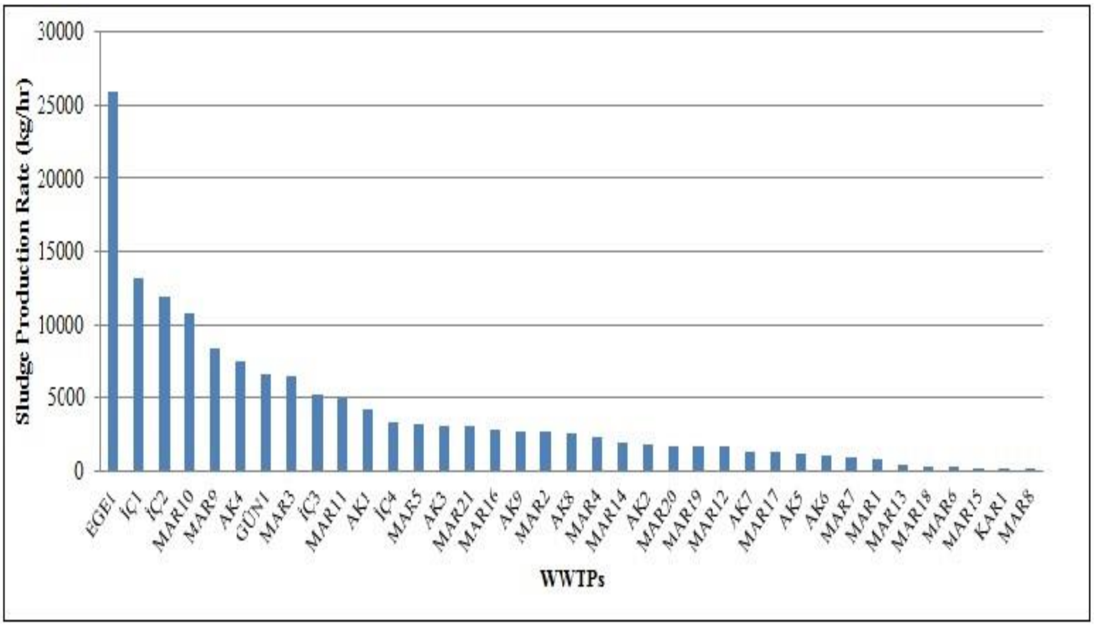


Figure 3.2 Sludge production rate in 37 WWTPs considered in the study

The locations of WWTPs were identified using Google Earth. Dimensions of the areas including all facilities of all WWTPs were estimated based on the scale of the maps provided in Google Earth. These areas are used in the optimization model as will be discussed in Section 3.2.4. Area views, sludge production rates, initial DS values and calculated facility areas (including the WWTP facility itself and the open area within the borders) are provided in Appendix-A. There were 2 WWTPs (MAR-8 and MAR-15), which were not included in Google Earth. In order to calculate the facility areas for these plants, a regression equation that relates facility areas to inflow rates (Figure 3.3) was used (TUBİTAK-KAMAG, 2013).

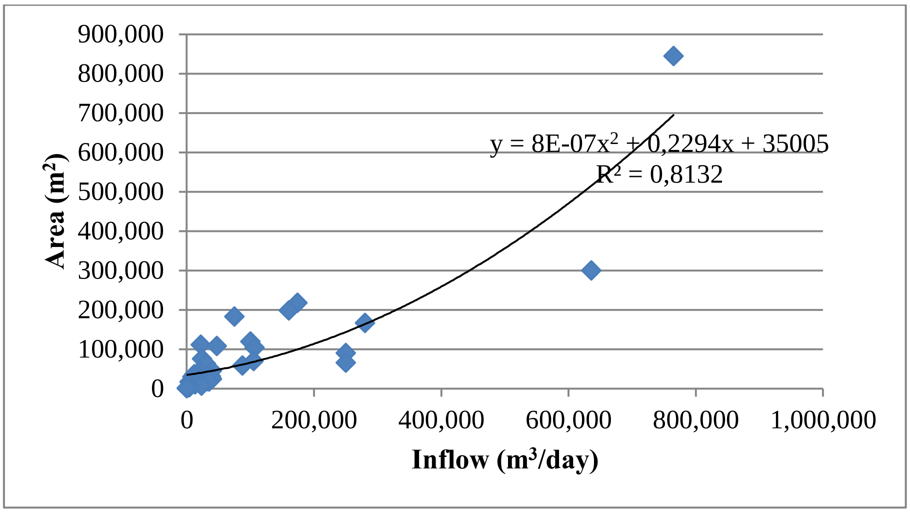


Figure 3.3 Relationship between WW flow rates versus the area of WWTPs

3.2. Evaluating Different Sludge Drying Techniques to Reach 90 %DS

As mentioned before, "Regulation on the use of Domestic and Urban Wastewater Treatment Sludges on Land" (2010) requires that sludge of WWTPs serving a population equivalent of one million or higher. The 37 WWTPs considered in this study are in this category. It is reported that thermal dryers and greenhouse solar dryers can dry the sludge up to 90%and 70% DS respectively (Flaga, 2007; Mangat et.al., 2009; Bux et.al., 2003; Ritterbusch et.al., 2012). Therefore, a greenhouse solar dryer should be supported with auxiliary heat in order to reach high dryness (i.e. 90% DS). In this study, solar panels are used as the main source as well as auxiliary heat source to reach the same final dryness as with the thermal dryers (90% DS). Evaluations are made based on capital and operating costs as well as area requirement. Solar systems are compared to different thermal dryer application options such as conventional thermal dryer and co-generation thermal dryer.

3.2.1. Cost Functions for Thermal Drying

Thermal dryers have ability to reach high DSC (≥ 90%DS) (Flaga, 2007). As mentioned before, costs of thermal drying for the 37 WWTPs considered in this study were calculated in TUBITAK KAMAG (108G167) project. In calculations, the assumption was that thermal dryer would dry the sludge up to 90% DS. Thermal drying costs include initial investment cost and cost of required energy for drying purpose (operational cost). The average prices of the thermal driers with different capacities were determined based on the quotes obtained from private companies (TUBİTAK-KAMAG, 2013). Required energy to reach a final DS was calculated based on thermodynamic equations.

The required energy for thermal drying depends mainly on the amount of water that needs to be evaporated from the sludge, fixed and volatile material contents of sludge, initial and final temperatures of sludge. The energy requirement can be estimated by a thermodynamic approach based on the study of “An Economic Evaluation of Sewage Sludge Drying and Incineration Processes.” (Schwarz, 1988). According to Schwarz (1988):

$$E_{d,i} = E_{w,i} + E_{w,evap,i} + E_{vo,i} + E_{f,i} \qquad \textbf{(3. 1)}$$

$$E_{d,i} = \Big(\big(m_{w,s,i} c_{p,w}(T_f - T_i)\big) + \big(m_{w,evap,i}(h_{v100} - h_{f100})\big) + \big(m_{vo,i} c_{p,vo}(T_f - T_i)\big) + \big(m_{f,i} c_{p,f}(T_f - T_i)\big)\Big)/0.9 \qquad \textbf{(3. 2)}$$

Where $E_{d,i}$ is the total energy required to dry sludge (kJ/hr), $E_{w,I}$ is the energy required to reach water in sludge to a temperature of T_f (kJ/hr), $E_{w,evap,i}$ is the energy required to evaporate water from sludge (kJ/hr), $E_{vo,i}$ is the energy required to reach volatile sludge to a temperature of T_f (kJ/hr), $E_{f,i}$ is the energy required to reach fixed sludge to a temperature of T_f (kJ/hr), $m_{w,i}$ is mass flow of the water in the sludge (kg/hr), $c_{p,w}$ is specific heat of water (kJ/ kg-C), T_f is final temperature (^oC), T_i is initial temperature (^oC), $m_{w,evap,i}$ is mass flow of the evaporated water in the sludge (kg/hr), h_{v100} is enthalpy of evaporate 100^{o}C (kJ/ kg), h_{f100} is enthalpy of liquid water at 100^{o}C (kJ/ kg), $m_{vo,i}$ is mass flow of the volatile solids in sludge (volatile solids which is assumed as 75% of total solids)(kg/hr), $c_{p,vo}$ is specific heat of volatile matter (kJ/ kg-C), $m_{f,i}$ is mass flow of the fixed solids in sludge (which is assumed as 25% of total solids) (kg/hr), $c_{p,f}$ is specific heat of fixed solids (kJ/ kg-C) and efficiency of thermal dryer is assumed as 90 % DS. Parameters and the values of thermodynamic constants used in equation 3.2 are given in Table 3.1.

Table 3.1 Constants and the values used in thermodynamic equation

Symbol	Description	Value	Unit	Reference
$c_{p,w}$	specific heat of water	4.19	(kJ/ kg-C)	(Sandler, 2006)
$c_{p,vo}$	specific heat of volatile matter	1.34	(kJ/ kg-C)	Schwarz (1988)
$c_{p,f}$	specific heat of fixed solids	0.88	(kJ/ kg-C)	Schwarz (1988)
T_f	final temperature	100	^oC	Schwarz (1988)
T_i	initial temperature	15	^oC	Schwarz (1988)
$h_{v,100}$	enthalpy of vapor at specified condition	2676	(kJ/ kg)	(Sandler, 2006)
$h_{f,100}$	enthalpy of liquid water at specified condition, here at initial condition	419.06	(kJ/ kg)	URL 7

The cost of the thermal dryer was obtained from TUBITAK KAMAG (108G167) project and calculated as the summation of the capital cost of thermal dryer unit and required energy which is obtained from Equation 3.3. It is given as:

$$Z_{TD,i} = Z_{D,i} + Z_{o,i} \quad \textbf{(3. 3)}$$

$$Z_{O,i} = E_{d,i} T c_{TL} \quad \textbf{(3. 4)}$$

Where $Z_{TD,I}$ is the total cost of thermal dryer (TL), $Z_{D,i}$ is the capital cost of thermal dryer unit (TL), $Z_{O,i}$ is the operating cost of thermal dryer unit based on the energy requirement (TL), $E_{d,i}$ is the total energy required to dry sludge (kJ/hr), T refers to time , c_{TL} is unit cost of electricity which is chosen 0.18 (TL/kWh) from TUBİTAK KAMAG,2013).

The required energy to run the thermal dryer can be supplied by electricity, natural gas or co-generation. Although conventional source is natural gas or coal, use of co-generation units enables the use of combustion energy as well as the waste heat from this exothermic reaction; thereby, energy use of cogeneration is lesser than that of traditional (conventional) thermal heating. Therefore, evaluation of required energy to dry sludge with thermal drying was performed both for the conventional system and the system with co-generation. For both, cost comparisons were made for short and long terms. In the conventional system, it was assumed that the required energy to run the system was obtained from electricity. The overall cost is calculated using Equation 3.3. For thermal drying with a co-generation unit the capital cost included the cost of the co-generation unit as well. The operating cost reflected the reduced external energy requirement due to co-generation (TUBİTAK-KAMAG, 2013).

3.2.2. Cost Functions for Greenhouse Solar Dryer

Design of the greenhouse solar dryer is based on evaporation rates in different regions. According to General Directorate of Turkish State Meteorology Service, mean pan evaporation rate in Turkey is 141.93 cm/yr (0.16 mm/hr). According to Wolfgang Brehm, who is contact person in Wendewolf Sludge Drying Company, the average evaporation rate in Turkey is about 0.2 to 0.3mm/hr (1700 to 2700 mm/yr, or 1.7 to 2.7 ton/m^2.yr), (personal communications, Wendewolf Company, 2012). These values are sufficient to use greenhouse solar driers for sludge drying. According to André Großer (personal communications, HUBER Dryer, 2012) the evaporation rate in Germany is 0.8 ton/yr and in Southern Cyprus 2.0 ton/yr. These countries use greenhouse driers for sludge drying. As sludge drying with GSD is feasible in these countries, it should be suitable for Turkey as well due to geographical location and climate. As André Großer stated (personal communications, 2012) retention time of sludge drying is not critical in the design of greenhouse driers. Rather, evaporation rate, feeding rates and thickness of sludge should be considered. Hence, considering geographical locations and climate, if it is feasible to dry sludge using greenhouse solar dryer in Germany, it can be an option for Turkey as well.

Determination of evaporation rate is crucial for the calculations of the performance of a greenhouse solar dryer. Pan evaporation rates alone, as provided by meteorological stations, are not sufficient to estimate drying performance because greenhouse solar dryers are closed systems and they can be controlled manually. According to the study “Optimal Control of Solar Sludge Dryers” by Seginer et al., (2007), mean evaporation rates of greenhouse solar dryers can be calculated as:

$$e_{V,i} = (\rho Q_v 1.964 * 10^{-11}) \left[\left(R_{o,i} + 1100\right)^{2.322} \left(T_{o,i} + 13\right)^{1.292} (Q_v)^{-0.577} (Q_m + 0.0001)^{0.013} \left(DS_{i,i} + 0.26\right)^{-0.353} \right] \quad \textbf{(3. 5)}$$

Where $e_{V,i}$ is the evaporation rate at location I (kg water/m^2.hr), ρ is the air density (1.13 kg/m^3), Q_v is the ventilation rate(m^3 (air) /m^2hr), $R_{o,i}$ is the solar radiation at location i (W/m^2), $T_{o,i}$ is the ambient air temperature at location I (^{o}C), Q_m is the air mixing rate (m^3 air/m^2.hr), $DS_{i,i}$ is the initial dry solid content (DSC) of the sludge at location i (kg solids/kg sludge).

Ventilation and mixing are most critical parameters to control evaporation rates. In this study, Q_v and Q_m are taken from Seginer et al. 2007. Constants used are given in Table 3.2.

Table 3.2 Constants of evaporation rate equation (Seginer et.al.,2007)

Symbol	Description	Value	Unit
ρ	Air density	1.13	kg/m^3
Q_v	Ventilation rate	150	m^3air/m^2 area/hr
Q_m	Air mixing rate	80	m^3air/m^2 area/hr

Solar radiation is the radiant energy emitted by the sun, particularly the electromagnetic energy (URL 3). The average annual solar radiation in Turkey is 1311 kW·h /(m^2·yr) or 3.6 kW·h /(m^2·d). Solar radiation levels of Turkey, especially Aegean and Mediterranean Regions, are comparable to those of Spain. Figure 3.4 shows the solar radiation distribution of Turkey. The mean solar radiation values at all stations in Turkey were obtained from the General Directorate of Turkish State Meteorology Service. Then interpolation was performed using inverse distance weighing in ArcGIS to obtain the $R_{o,i}$ values in Equation 3.5. Figure 3.5 shows the interpolation obtained using long term average values.

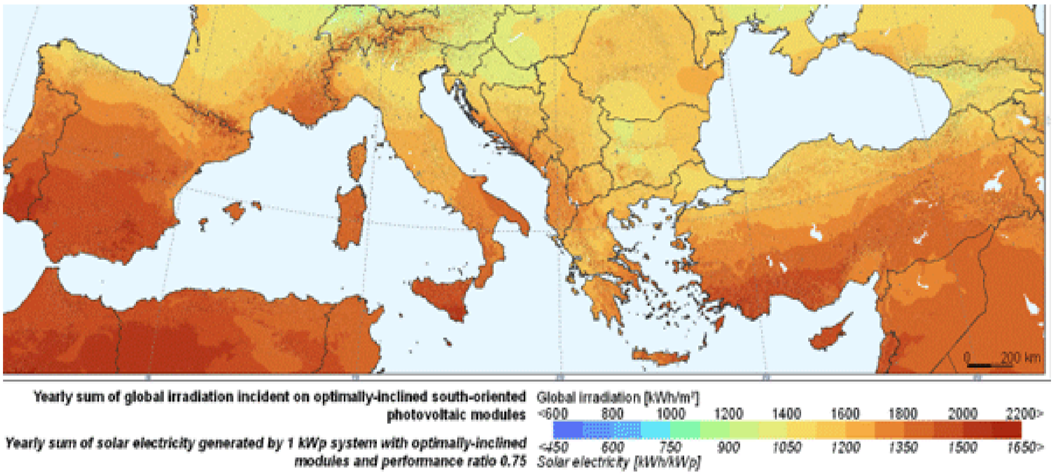


Figure 3.4 Solar radiation distribution of Turkey (URL 5)

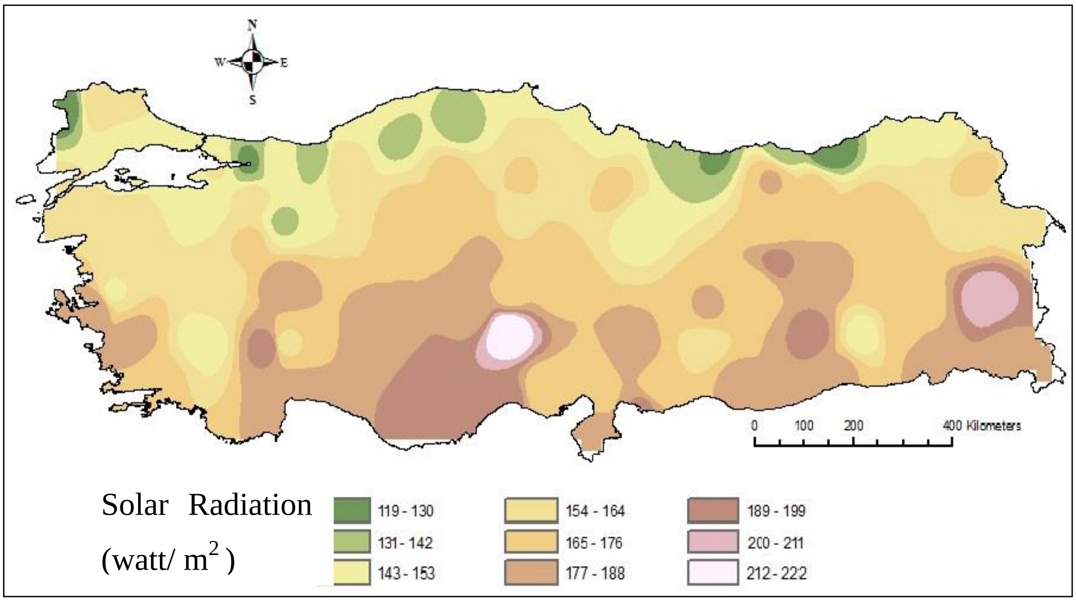


Figure 3.5 Interpolated long term solar radiation values in Turkey

Ambient air temperature is one of the parameters used in calculation of the evaporation rate (Equation 3.5). The mean temperature in Turkey varies spatially due to different climatic conditions. Mean ambient air temperatures measured at meteorological stations were obtained from the General Directorate of Turkish State Meteorology Service. Then interpolation was conducted using inverse distance weighing in ArcGIS to obtain the distribution in Figure 3.6. Mean temperatures at the considered WWTPs range between 19 and 10 ^{o}C.

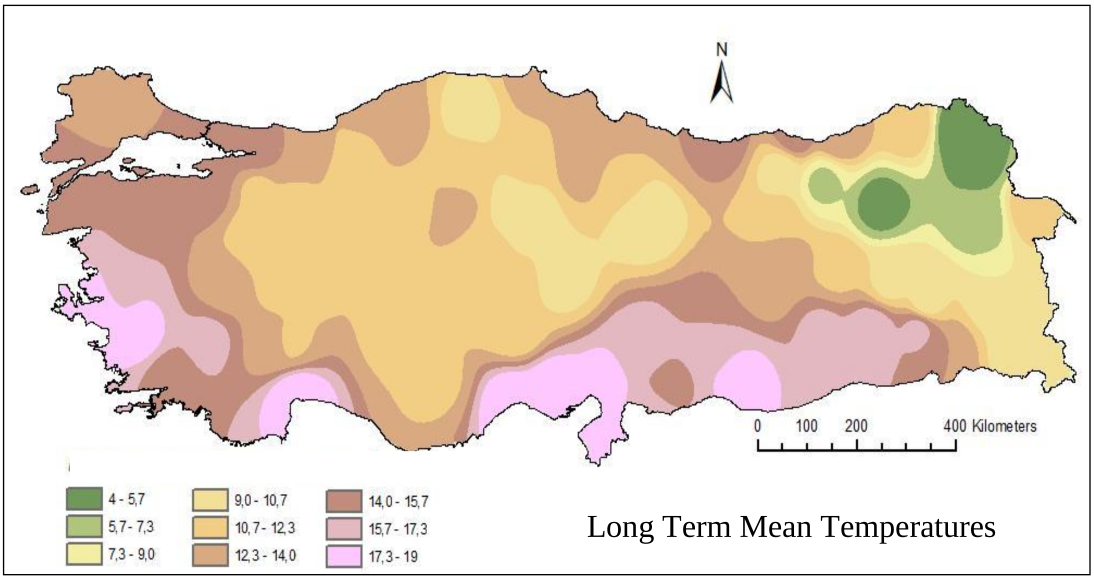


Figure 3.6 Long term mean temperatures in Turkey

The drying bed area is calculated based on $E_{V,i}$ and the target sludge dryness. Then the capital (construction) cost is calculated based on drying bed area. With these assumptions, the capital cost of the greenhouse solar dryer is calculated as:

$$Z_{C\_GSD,i} = A_{C\_GSD,i}\, C_{C_{GSD},i} \tag{3. 6}$$

$$A_{GSD,i} = {}^{m_{e,i}}/_{e_{V,i}} \tag{3. 7}$$

$$m_{\boldsymbol{e},\boldsymbol{i}} = m_{\boldsymbol{s},\boldsymbol{i}} - \left(m_{\boldsymbol{s},\boldsymbol{i}} \frac{DS_i}{DS_m}\right) \tag{3. 8}$$

where $Z_{C\_GSD,I}$ is construction cost of GSD i (TL), $A_{GSD,i}$ is the required base area of the greenhouse solar dryer at WWTP i (m^2), $C_{CGSD,I}$ is the unit construction cost of the greenhouse solar dyer i (TL/m^2), $m_{e,i}$ is the amount of water that should be evaporated to reach the desired sludge dry matter content at WWTP i (kg/hr),$e_{V,i}$ is the evaporation rate at location i (kg water/m^2.hr), $m_{s,i}$ is the wet sludge loading rate (kg/hr), DS_i is initial dry solid and DS_m is intermediate dry solid (DSC achieved in GSD). According to the quotes obtained from private companies (personal communications HUBER, WENDEWOLF, 2013), $C_{CGSD,i}$ ranges between 250 € /m^2 and 350 € /m^2. In this study, it was taken as 300 € /m^2.

In calculation of the operational cost of the greenhouse solar dryer, energy consumption was the focus. In a greenhouse solar dryer, ventilation and mixing of sludge consume energy. The energy required for mixing and ventilation is given as 15-25 kWh/t-water evaporated (Huber, 2013; Wendewolf, 2013). In some studies the values range between 20 and 40 kWh per 1 ton of water evaporated (Ritterbusch et al., 2012). Also, in the study in Nicaragua by Scharenberg et al. (2010) energy for ventilation was 20 kWh of energy for evaporation of one ton of water. In this study, the mixing and ventilation energy was taken as 20 kWh/ton of evaporated water. With this assumption, the operational cost function for the greenhouse solar dryer is given as:

$$Z_{O\_GSD,i} = e_{GSD}\, m_{e,i}\, c_{ea} \qquad \textbf{(3.9)}$$

Where $Z_{O\_GSD,i}$ is the cost of operation of greenhouse solar dryer at WWTP i (TL), e_{GSD} is unit energy consumption for ventilation and mixing per ton of evaporated water (20 kWh/ton water), $m_{e,i}$ is the mass of evaporated water from sludge at WWTP(ton water), c_{ea} is unit average energy cost (TL/kWh).

3.2.3 Cost Functions for Solar Panels for Sludge Drying

Solar panels can be used both as the auxiliary heat source for a greenhouse solar dryer and the main energy source of a drying unit. Solar panel use is an option instead of using fossil fuel in a thermal dryer. Required solar panel area to install and cost of solar panels are calculated based on the required energy to evaporate a given amount of water from sludge and sunshine duration in the region of concern.

The amount of required energy that should be supplied via solar panels was calculated using Equation 3.1. It must be emphasized that solar panels can operate during sunshine duration; hence, required power should be calculated based on the sunshine duration (Equation 3.10). Mean sunshine durations in Turkey was provided from General Directorate of Turkish State Meteorology Service, which is shown in Figure 3.7.

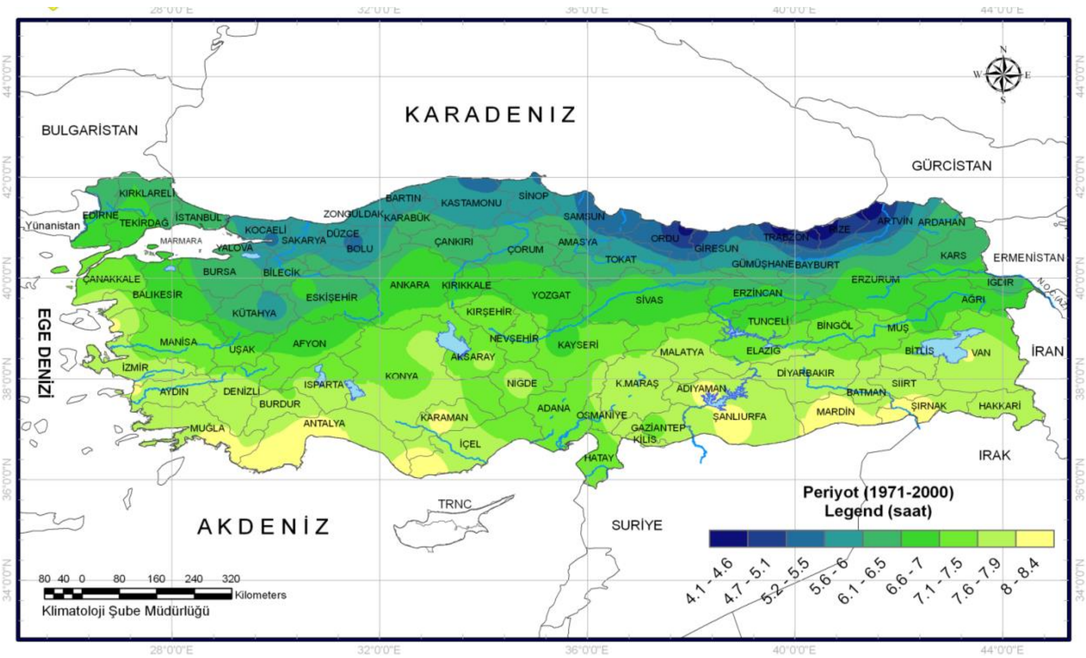


Figure 3.7 Sunshine duration values of Turkey estimated based on long term date

$$P_{WWTP,i} = \frac{E_{Dd,i}}{\text{ts,i}\ (hr)} \qquad \textbf{(3. 10)}$$

Where $P_{WWTP,i}$ is the required power for WWTP (kW),$E_{Dd,i}$ is daily required energy (kJ) and $t_{s,i}$is sunshine duration (hr).

Area for installation of solar panels and cost of the solar panels depend only on the power need for drying. The unit costs and capacities of solar panels of different manufacturers were obtained from private companies. Table 3.3 summarizes the properties of solar panels and their costs.

Table 3.3 Properties of panels sold in the market

Company	Power (Watt)	Cost of panel	Unit cost ($/Watt)	Reference
Aten solar	50	$92.50	$1.85	URL 8
Evergreen	195	$ 555.97	$ 2.85	URL 8
Brightwatts	120	$ 358.00	$ 2,98	URL 8
BP solar	175	$ 532.97	$ 3.05	URL 8
Kyocera	180	$ 594.00	$ 3,30	URL 9
Sharp	175	$ 696.50	$ 3.98	URL 9
Mitsubishi	125	$ 525.00	$ 4.20	URL 9
TurkWatt (Grid on systems)	-	-	€1.1-1.7	URL 10
TurkWatt with battery (Grid off systems)	-	-	€3.2-3.4	URL 10

Solar panels and photovoltaic batteries can be applied as both grid on and grid off systems. A grid-on system means that produced energy is transferred to an electricity network; where as a grid-off system accumulates produced energy in an accumulator (Chamber of electrical engineering, n.d.). A grid-on system is the most popular choice for solar panel use. This system can profit from the electricity tariff price difference between night and day. Also, installation of a grid-on system is generally cheaper than a grid-off system. Grid-off systems use accumulators to store produced energy, which makes the system expensive.

In this study grid-on systems are used when GSD and solar panels were used in combination. Cost of the panel with all auxiliaries (panel, converter, cables, etc.) for a grid-on system is 1.4 €/W whereas, cost of grid off systems with all requirements (accumulator, cables, converter etc.) is 3.3 €/W (URL 10). The daily exchange rate is assumed as 2.33 TL/€ as in TUBİTAK-KAMAG Project so that costs obtained in that project for thermal dryers can be compared with the ones obtained for GSD and solar panels in this study. As obtained from private companies (Table 3.3), the average area of a solar panel is 1.77m^2/W. In this system, it is assumed that the government incentive for the use of renewable energy obtained. Turkish government applies different electricity tariffs at different time periods in a day (Table 3.4). Moreover, use of renewable energy sources is encouraged. It is possible to sell the electricity produced to the national electricity network at the price stated in Table 3.4. Therefore, it is possible to transfer the electricity produced by solar panels during daytime at a rate higher than the unit electricity cost at night time. In Table 3.4, the first three rows represent the unit electricity costs a plant would pay to purchase electricity while the last row is the unit sale price (benefit) when the plant transfers electricity to the national network.

Table 3.4. Electric Tariff during the day

Time schedule	TL/kWh	Reference
06.00 am- 17.00 pm	0,2212	URL 6
17.00pm- 22.00 pm	0,3636	URL 6
22.00pm- 06.00 am	0,1185	URL 6
Renewable energy sale price to the national network	0.2394	Law of renewable energy sources being used to produce electricity, 2005

Although solar panels and photovoltaic batteries can be regarded as unlimited and environmentally friendly energy sources, they are expensive. Therefore, it may take long time to pay-off their high installation and investment costs. However, the studies on solar panels show both decrement in costs and increment in performance of panels are expected in time. In addition, policies that encourage the use of renewable energy sources by governments decrease the pay-off time (Yavuz et.al., 2013;Chamber of electrical engineering, n.d.).

3.2.4. Optimization Model for Greenhouse Solar Dryer Supported with Solar Panels

The drying performance of a greenhouse solar dryer, as mentioned in Chapter 2, cannot go beyond 70% DS on average (Bux et.al., 2003). Therefore, greenhouse solar dryers should be supported with auxiliary heat to reach 90% DS. This can be achieved through solar panels. The proposed system is illustrated in Figure 3.8. The system can work as grid-on and grid-off.

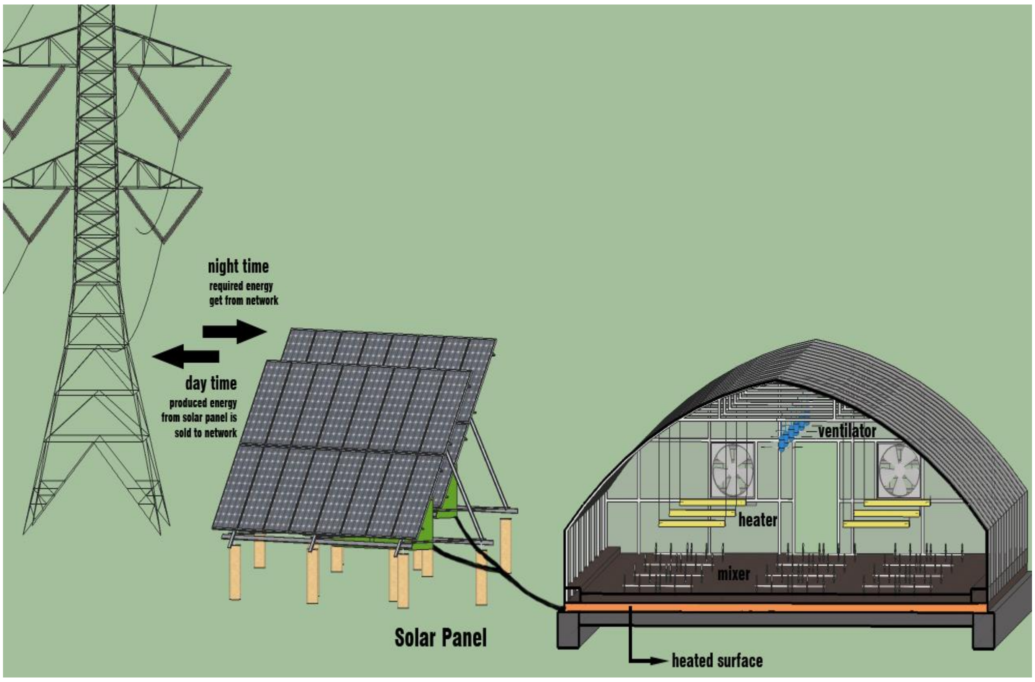


Figure 3.8. An illustration of the suggested greenhouse solar dryer supported with solar panels as the auxiliary heat source

The system was evaluated based on the area required for solar panels and greenhouse solar dryer. Water removal rate in greenhouse solar dryers is an indicative parameter for the total cost and area requirement. In this study it was assumed that the amount of water that should be evaporated to reach at most 70%DS impacts the area of the greenhouse dryer itself while the amount of water that should further be evaporated to reach 90% DS impacts the additional energy requirement and therefore the area of solar panels.

An optimization model was used in order to determine the costs of sludge drying with a greenhouse solar dryer supported with solar panels in which the relative energies supplied (and therefore the costs) by the greenhouse solar dryer and solar panels are a function of an intermediate dry solids (DS_m) (the decision variable of the optimization model).Optimization helps to find the best solution among all the feasible solutions. The objective of the optimization model developed in this study aims at minimizing construction and operation costs of sludge drying while meeting system constraints. The optimization model is developed as a linear model and Excel-Solver is used to reach the optimal solution which is a readily available add-in in Microsoft Excel. Best solutions for different cases are plotted using Matlab.

In finding the best solution, different optimization models with the same objective function but different system constraints were used. The objective function of the optimization models is given in Equation 3.12. This equation consists of cost of greenhouse solar dryer and cost of solar panel. The total cost of a greenhouse solar dryer is consisted of construction and operation costs (Equation 3.13). The total solar panel cost includes the capital cost of required solar panel to supply the energy required to dry sludge both in day time and night time (Equation 3.14). Because solar radiation (Ro) is zero at night time, evaporation rate and evaporated water amount decrease. As a result, auxiliary energy is required at night time to continue with drying. For that reason, required energies of the system at night time and daytime were separately calculated. By this way it would be possible to determine the quantity of auxiliary energy required at night time. Due to the energy tariff in Turkey (Table 3.4), the required auxiliary energy at night time is produced during the day and sold to the network at a beneficial price. Then at night time, the electricity is purchased from the network at a lower cost, which in turn is expected to decrease the overall operational costs of the system. Therefore, reversible counter is used in order to reduce the cost of solar panels. The Energy Market Regulatory Authority (EMRA) applies different tariffs for day and night time. Moreover, a different tariff is valid for produced renewable energy. In this study, it is assumed that during day time the energy produced is sold at the tariff of renewable energy. The energy required in night time is purchased at the cheaper tariff at night time.

$$Min\ Z_{COST} = Z_{GSD,i} + Z_{SP,i} \quad \textbf{(3. 11)}$$

Where Z_{COST} is the total construction cost of solar panel and solar drying bed (TL), $Z_{GSD,i}$ is the total construction and operation cost of greenhouse solar drying unit (TL), $Z_{SP,i}$ is the construction cost of solar panel(TL).

$$Z_{GSD,i} = Z_{C\_GSD,i} + Z_{O\_GSD,i} \quad \textbf{(3. 12)}$$

Where $Z_{C_GSD,i}$is construction cost of GSD i(TL) and $Z_{O\_GSD,i}$ is the operation cost of GSD (TL).

$$Z_{SP,i} = Z_{C\_SP\_D,i} + Z_{C\_SP\_N,i} \quad \textbf{(3. 13)}$$

Where $Z_{C\_SP\_D,i}$ is the construction cost of solar panel during day time (TL) and $Z_{C\_SP\_N,i}$ is the construction cost of solar panel during night time (TL).

$$Z_{C\_SP\_D,i} = \frac{C_{SP}}{t_{s,i}} E_{d\_D,i} \quad \textbf{(3. 14)}$$

Where C_{SP} is the unit cost of panel (TL/watt) and ts,i is the sunshine duration hours at location I (hr), $E_{d\_D,i}$ is the energy requirement during day time to heat sludge (kJ/hr).

$$E_{d\_D,i} = \left(E_{w,i} + E_{e,i} + E_{vo,i} + E_{f,i}\right)_D / n \quad \textbf{(3. 15)}$$

Where $E_{w,i}$ is the energy requirement to heat up the water content of sludge (kJ/hr), $E_{e,i}$ is the energy requirement to evaporate a given amount of water from sludge (kJ/hr), $E_{vo,i}$ is the energy requirement to heat up the volatile solids content of sludge to T_f (kJ/hr), $E_{f,i}$ is the energy requirement to heat up fixed solids in sludge to T_f (solid) (kJ/hr) and n is the energy conversion efficiency factor (0.9).

$$E_{w,i} = m_{w,i} c_{p,w} (\mathrm{T_f} - \mathrm{T_i}) \quad \textbf{(3. 16)}$$

$$E_{w,evap,i} = m_{w,evap,i}\left(h_v - h_f\right) \quad \textbf{(3. 17)}$$

$$E_{vo,i} = m_{vo,i}c_{p,vo}(\mathrm{T_f} - \mathrm{T_i}) \quad \textbf{(3. 18)}$$

$$E_{f,i} = m_{f,i}c_{p,f}\left(T_f - T_i\right) \quad \textbf{(3. 19)}$$

Where $m_{w,i}$ is the loading rate for the initial water content of sludge (kg/hr), c_{p_w} is the specific heat of water (kJ/ kg ^oC), T_f is the final temperature (^oC) and T_i is the initial temperature (^oC).$m_{w,evap,i}$ is the amount of water that is/should be evaporated (kg/hr), h_v is enthalpy of water vapor at given conditions (kJ/ kg), h_f is the enthalpy of liquid water at given conditions (kJ/ kg), $m_{vo,i}$ is the amount of volatile solids in sludge (kg/hr), $c_{p,vo}$ is specific heat of volatile matter (kJ/ kg ^oC) $m_{f,I}$ is the amount of fixed (solid) solids in sludge (kg/hr), $c_{p,f}$ is specific heat of fixed matter (kJ/ kg ^oC),

$$m_{w,i} = m_{s,i} - \left(m_{s,i}\sigma_{i,i}\right) \quad \textbf{(3. 20)}$$

$$m_{vo,i} = m_{s,i}DS_{i,i}(0.75) \quad \textbf{(3. 21)}$$

$$m_{f,i} = m_{s,i}DS_{i,i}(0.25) \quad \textbf{(3. 22)}$$

$$m_{e,i} = \left(m_{s,i} - \frac{m_{s,i}DS_{i,i}}{DS_f}\right) \quad \textbf{(3. 23)}$$

Where $m_{s,i}$ is the wet sludge loading rate (kg/hr) $DS_{,i,i}$ is the dry matter content of sludge produced in plant i(kg dry sludge/kg wet sludge) and $DS_{,f,i}$ is the final matter content of sludge produced in plant i(kg dry sludge/ kg wet sludge).

The equation 3.15 calculates required cost to reach 90%DS and Equation 3.9 calculates operation energy cost. These two equations are combined at below equation for day time.

$$Z_{Ct\_SP\_D,i} = \frac{c_{SP}}{t_{S,i}}\left(\left(\left(\left(m_{w,i} - \left(A_{GSD}e_{Vd,i}\right)\right)c_{p\_w}\left(T_f - T_i\right)\right) + E_{w,eva,,D,i} + E_{vo,i} + E_{f,i}\right)_D t_{s,i} + \left(\left(A_{GSD}e_{Vd,i}\right)E_{Ven}\right)\right) \quad \textbf{(3. 24)}$$

Where $Z_{Ct\_SP\_D,i}$ is total panel cost used during day time, c_{SP} is unit cost of panel (TL/watt) $t_{s,i}$ is sunshine duration hours at location i (hr) $m_{w,i}$ is initial mass flow of the water in sludge (kg/hr), A_{GSD} is area of GSD (m^2), $e_{Vd,i}$ is evaporation rate during day time ($kg/m^2.hr$), $c_{p,w}$ is specific heat of water (kJ/ kg-C), T_f is final temperature (^oC) and T_i is initial temperature (^oC), $E_{w,eva,D,i}$ is required energy to evaporate remaining water for reaching 90% DS during day time (kJ/hr), $E_{vo,i}$ is the energy required to heat up volatile sludge till T_f (kJ/hr), $E_{f,i}$ is the energy required to heat up fixed sludge till T_f and E_{Ven} is the energy required to ventilation to evaporate 1 ton water from sludge (kJ).

$$Z_{C\_SP\_N,i} = \frac{c_{SP}c_{en}}{t_{s,i}c_{er}}E_{d\_N,i} \quad \textbf{(3. 25)}$$

Where $Z_{C\_SP\_N,i}$ is the construction cost of solar panel during night time (TL), C_{SP} is the unit cost of panel (TL/watt), $t_{s,i}$ is the sunshine duration hours at location i (hr), c_{en} is cost of electricity at night time (0.1185 TL/kWh), c_{er} is cost of electricity supplied from renewable solar energy (0.2394 TL/kWh) and $E_{d\_N,i}$ is the energy requirement during night time to heat sludge (kJ/hr).

$$E_{d\_N,i} = \left(E_{w,i} + E_{e,i} + E_{vo,i} + E_{f,i}\right)_N / n \quad \textbf{(3. 26)}$$

Similar to equation 3.25, Equation 3.28 calculates total energy cost during night time.

$$Z_{Ct\_SP\_N,i} = \frac{c_{SP}c_{en}}{t_{S,i}c_{er}}\left(\left(\left(\left(m_{w,i} - \left(A_{GSD}e_{Vn,i}\right)\right)c_{p\_w}\left(T_f - T_i\right)\right) + E_{w,eva,N} + E_{vo,i} + E_{f,i}\right)_N t_{N,i} + \left(\left(A_{GSD}e_{VN,i}\right)E_{Ven}\right)\right) \quad \textbf{(3. 27)}$$

Where $Z_{Ct\_SP\_N,i}$ is total panel cost used during night time, C_{SP} is unit cost of panel (TL/watt),$t_{s,i}$ is sunshine duration hours at location i (hr), c_{en} is cost of electricity at night time (0.1185 TL/kWh), c_{er} is cost of electricity supplied from renewable solar energy (0.2394 TL/kWh),$m_{w,i}$ is initial mass flow of the water in the sludge (kg/hr), A_{GSD} is area of GSD (m^2), $e_{Vn,i}$ is evaporation rate during night time (kg/m^2.hr), $c_{p,w}$ is specific heat of water (kJ/ kg-C), T_f is final temperature (^oC) and T_i is initial temperature (^oC), $E_{w,eva,N}$ is required energy to evaporated remain water for reaching 90% DS during night time (kJ/hr),$E_{vo,i}$ is the energy required to heat up volatile sludge till T_f (kJ/hr), $E_{f,i}$ is the energy required to heat up fixed sludge till T_f, $t_{N,i}$ is night time duration hours at location i (hr) and E_{Ven} is the energy required to ventilation to evaporate 1 ton water from sludge (kJ).

Equation 3.15 and 3.26 calculate the panel costs for day and night time, respectively. Equation 3.16 and 3.27 are used to calculate the required energy at day and night times, respectively. Equation 3.17, 3.18 3.19 and 3.20 are used to determine the energy required to heat the water content of sludge, amount of water that should be removed to reach target dryness, to heat the volatile content of sludge to a given temperature, and to heat up the fixed component of sludge to reach final temperature. Equation 3.21 3.22 3.23 and 3.24 define the water content of sludge, volatile content of sludge, fixed content of sludge and the removed water amount of sludge, respectively. Finally, Equations 3.25 and 3.28 show the extended forms of Equations 3.15 and 3.26, respectively. The open form of optimization function (Eq 3.12) is below equation;

$$MinZ_{COST} = \left(\left(\left(\left({}^{m_{e,i}}/_{e_{V,i}} \right) C_{C_{GSD},i} \right) + \left(e_{GSD} m_{e,i} c_{ea} \right) \right) + \left(\left(\frac{c_{SP}}{t_{S,i}} \left(\left(\left(\left(m_{w,i} - \left(A_{GSD,i} e_{Vd,i} \right) \right) c_{p\_w} \left(T_f - T_i \right) \right) + E_{w,eva,D,i} + E_{vo,i} + E_{f,i} \right)_D t_{s,i} + \left(\left(A_{GSD,i} e_{Vd,i} \right) E_{Ven} \right) \right) \right) + \left(\frac{c_{SP} c_{en}}{t_{S,i} c_{er}} \left(\left(\left(\left(m_{w,i} - \left(A_{GSD,i} e_{Vn,i} \right) \right) c_{p\_w} \left(T_f - T_i \right) \right) + E_{w,eva,N,i} + E_{vo,i} + E_{f,i} \right)_N t_{N,i} + \left(\left(A_{GSD,i} e_{VN,i} \right) E_{Ven} \right) \right) \right) \right) \right) \quad (3.\ 28)$$

Table 3.5 presents the constant values used in the optimization model functions. Construction costs of greenhouse solar dryer and cost of panels include both workmanship and other auxiliaries (e.g. converter of a solar panel).

Table 3.5 Cost values in use optimization equation

Symbol	Description	Value	Unit	Reference
C_C	Construction cost of GSD	300	€/ m^2	Average of the values obtained from private companies
C_{SP}	Cost of panel	1.4	€/W	Average of the values obtained from private companies
c_{er}	Cost of electricity supplied from renewable solar energy	0.2394	TL/kWh	Law of renewable energy sources being used to produce electricity (2005)
c_{en}	Cost of electricity at night time	0.1185	TL/kWh	URL 6, 2013

In the optimization model, the evaporation rate of water from sludge is assumed as steady in the time period considered. Yet, different evaporation rates are considered in daytime and at night. In the day time, Ro is accepted as mean of daily radiation value and E_{d_D} is calculated. At night time Ro is accepted as zero and E_{d_N} is calculated. The greenhouse solar dryer area was obtained based on the evaporation rate during day time (E_{d_D}). The dry solids content reached in the greenhouse solar drying system is defined as the "intermediate dry solids content", which is the decision variable in the optimization model. The intermediate dry solids content (DS_m) becomes the initial dryness value for the sludge that would further be dried to 90% DS using the energy obtained from solar panels.

The objective function is subject to several system constraints including the limits on DS_m, total area available for drying systems and different area constraints for the Greenhouse Dryer. These constraints are given as

$$DS_i \leq DS_m \leq 70\% \quad \textbf{(3. 29)}$$

$$A_{GSD,i} + A_{SP,i} \leq A_{WWTP,I} \quad \textbf{(3. 30)}$$

$$A_{GSD,i} \leq 20{,}000 \quad \textbf{(3. 31)}$$

$$A_{GSD,i} \leq 0.05 * A_{WWTP,i} \quad \textbf{(3. 32)}$$

$$A_{GSD,i} \leq 0.10 * A_{WWTP,i} \quad \textbf{(3. 33)}$$

Where $A_{WWTP,i}$ is the area of treatment plant i estimated from Google Earth (Appendix A). Equation 3.30 ensures that intermediate dryness cannot be lower than the initial dryness and cannot go beyond 70% dryness, which is the upper DSC that can be achieved by a greenhouse solar dryer. Equation 3.31 ensures that the total area covered by solar panels and greenhouse solar dryer cannot be larger than the actual area of the WWTP. Therefore, it was assumed that the area allocated to the WWTP could be doubled at most relative to its current area to accommodate drying units and solar panels. Area limitation is a constraint in some regions of Turkey, especially in

Marmara and Karadeniz regions. Moreover, a WWTP operator may not prefer a sludge drying area larger than the treatment plant itself. Different area constraints are used to limit the area that can be allocated to the greenhouse dryer. Only one of the Equations 3.32, 3.33, and 3.34 is used as a constraint in a given optimization run. Equation 3.32 states that the area of a greenhouse solar dryer cannot be larger than the largest facility available in the world so far (Palma de Mallorca greenhouse solar dryer, 20,000 m^2). Equations 3.33 and 3.34 assume that the area that can be allocated to the greenhouse solar dryer cannot be more than 5 % and 10 % of the WWTP areas (Appendix I). This area limitation constraint is used to understand the impact of the available area for sludge drying on costs and feasibility of sludge drying with GSD supported with solar panels. In evaluations, the constraint on the upper limit for DSC that can be achieved by a solar dryer was decreased to 60 %, 50 % and 40 %, as well.

In evaluations as well as the optimization model which determined the DS_m to minimize the drying procedure using the combination of greenhouse solar dryer and solar panels, costs are calculated assuming different upper limits for DS_m values. In cost calculations, 4 different scenarios are considered based on the constraint on the area allocated to GSD. In all scenarios, it was assumed that the final dried sludge will have 90% DS and the total area covered by GSD and solar panels cannot be more than the area occupied by a given WWTP. In D90C1, area constraint given by Equation 3.31 was considered. In D90C2, area constraints were given by Equation 3.31 and Equation 3.32. In D90C3, Equation 3.31 and Equation 3.33are considered. Finally in D90C4, Equation 3.31 and 3.34 are included as the area constraints. In these scenarios it was assumed that when solar panels are used to provide auxiliary energy, they can be built in any suitable place that can have access to sun including rooftops.

3.2.4.1. Scenarios

D90C1: Sludge is assumed to dry until 90 % DS. Solar panels are assumed to produce required energy for all day during solar duration time. Equation 3.30 and

3.31 are applied as DS and area constraints and optimum cost value is examined in gradually by decreasing DS_m value. The goal of this scenario is examining effect of DS_m value on cost and area requirement.

D90C2: Like D90C1, sludge is assumed to dry until 90%DS and solar panels are assumed to produce required energy for all day during solar duration time. Equation 3.30 and 3.32 are applied as area constraint. DS_m value is assumed not be exceeded 70 % DS. In this scenario, GSD area is limited with 20,000 m^2 because the biggest greenhouse solar dryer area in the world is Palma de Mallorca greenhouse solar dryer which is 20,000 m^2 so the greenhouse solar dryer area obtained should be less than this value.

D90C3 &D90C4: Like previous scenarios, sludge is assumed to dry until90%DS and solar panels are assumed to produce required energy for all day during solar duration time. Equation 3.30 is applied as DS constraint; Equation 3.33 and equation 3.34 are applied as area constraint to D90C3 and D90C4, respectively. The aims of these scenarios are determining importance of area requirement to reach desirable DS.

3.2.4.2. Evaluating Solar Panel System in GSD by Using Only Solar Duration Time:

Previous scenarios weren't thought solar panel covered area. Required area was assumed to handle by using rooftops, free places or installed solar panels fields at suitable places. Figure 3.9 shows some examples about applying solar panels.

Figure 3.9 Some examples about applying solar panel (URL 14; URL 15; URL 16; URL 17; URL 18)

The previous scenarios also were assumed that GSD with solar panels work non-stop and dried sludge in a short time. Nevertheless, wet sludge can wait in GSD system 2-3 days. In this scenario, required energy in night time is ignored and required energy was calculated only for day time to reach 90 % DS. DS_m value also is accepted 70 % DS.

CHAPTER 4

RESULTS AND DISCUSSION

Sludge production rates of 37 WWTPs ranged between 25,901 and 4 kg/hr. Therefore, evaluations were made for WWTPs of varying capacities. For all drying scenarios considered area requirements and costs were determined. The greenhouse solar dryer system supported with solar panels consisted of 4 different optimization scenarios (D90C1, D90C2, D90C3, D90C4) based on different area constraints for the greenhouse solar dryer.

All WWTPs were examined for all scenarios. The most cost efficient scenarios were compared with conventional and co-generation thermal dryer (yearly and long years such as at the end of 28 years). In all scenarios, solar panels were assumed to produce required day and night time energy during day time to be equalizing the system to thermal dryer. Because of that, GSD supported with solar panels were assumed to produce only day time required energy in order to increase availability of solar panels. As climate drastically affects the performance for both greenhouse solar dryer and solar panels, the results were compared with examples from the known treatments plants located in places with similar climate in the world.

4.1. Evaluating Greenhouse Solar Dryer Supported with Solar Panels as Auxiliary Energy Source

As mention in Chapter 2, greenhouse solar dryer cannot reach 90 % DS by itself. Therefore, it needs auxiliary heat. This study assumed that greenhouse solar dryers were supported with solar panels to increase dryness. Scenarios D90C1, D90C2, D90C3 and D90C4 evaluated the change in costs for different area constraints.

4.1.1. Results of D90C1

D90C1 is the core scenario upon which D90C2, D90C3, and D90C4 are developed. The main equation covering D90C1 is the objective function described in Equation 3.21. This scenario calculates the minimum cost of greenhouse solar dryer system supported with solar panel where intermediate dry solids content (DS_m) is the decision variable. The assumption of the D90C1 is that sludge could reach maximum 70 % DS in greenhouse solar dryer unit and remaining water could be evaporated with auxiliary heat from solar panel to reach 90% DS. The constraint of the optimization function is area. Necessary total areas for greenhouse solar dryer and solar panels are less than or equal to the projection views of WWTPs obtained from Google Earth, which is given in Appendix-A.

The scenario D90C1 calculates the minimum cost of installation of greenhouse solar dryer and solar panel for 37 WWTPs. These 37 WWTPs have different sludge production rates (25,901- 4 kg/h) and initial dry solids content (DS_i). According to the optimization results, for all WWTPs the minimum costs of greenhouse solar dryer supported with solar panel resulted in WWTPs where DS_m values were maximum (70 % DS). Figure 4.1 shows the optimal costs and areas covered by the drying system for all WWTPs. The numbers refer to name of WWTPs, Appendix-B gives which number belongs to which WWTPs.

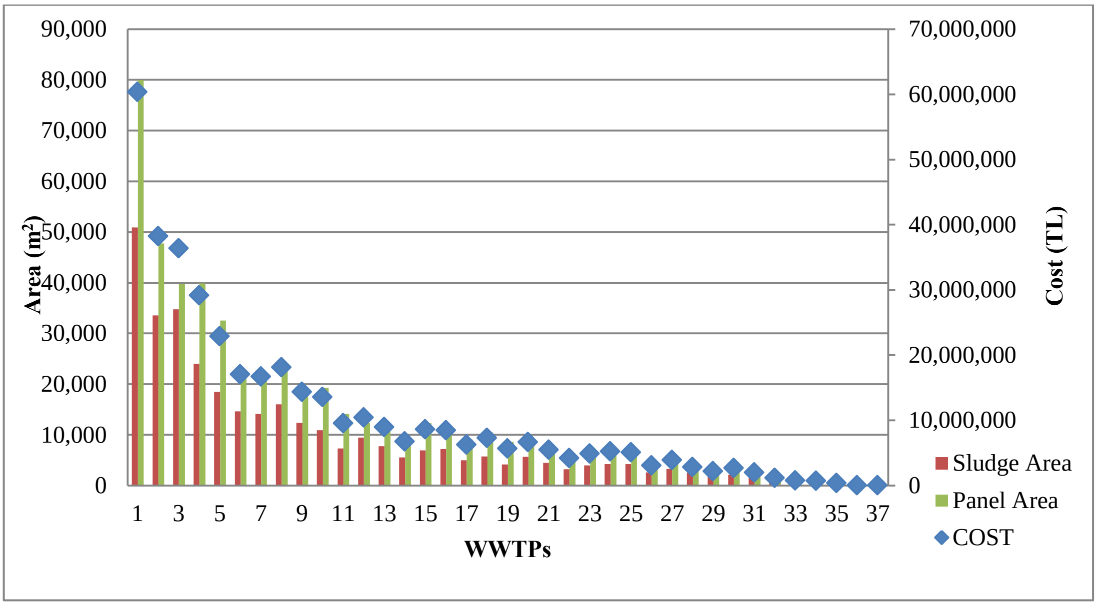


Figure 4.1 Required greenhouse solar dryer area, solar panel area and installation costs for 37 WWTP

The cost calculated by optimization function changes between 60,359,216 TL to 10,772 TL when DS_m were 70 % DS for each WWTP. On average, 58% of the total cost consisted of greenhouse solar dryer cost and the rest was solar panel cost. Figure 4.2 shows total cost distribution in terms of greenhouse solar dryer and solar panel costs. At the same final dry solids content, necessary GSD areas ranged between 50,902 $m^2$and 8 m^2. Solar panel area requirement ranged between 79,957.39 and 15.91 m^2. It is obvious that when sludge production increases, required cost, GSD area and panel area would increase. Additionally, the optimization revealed that required solar panel area was always larger than greenhouse solar dryer area.

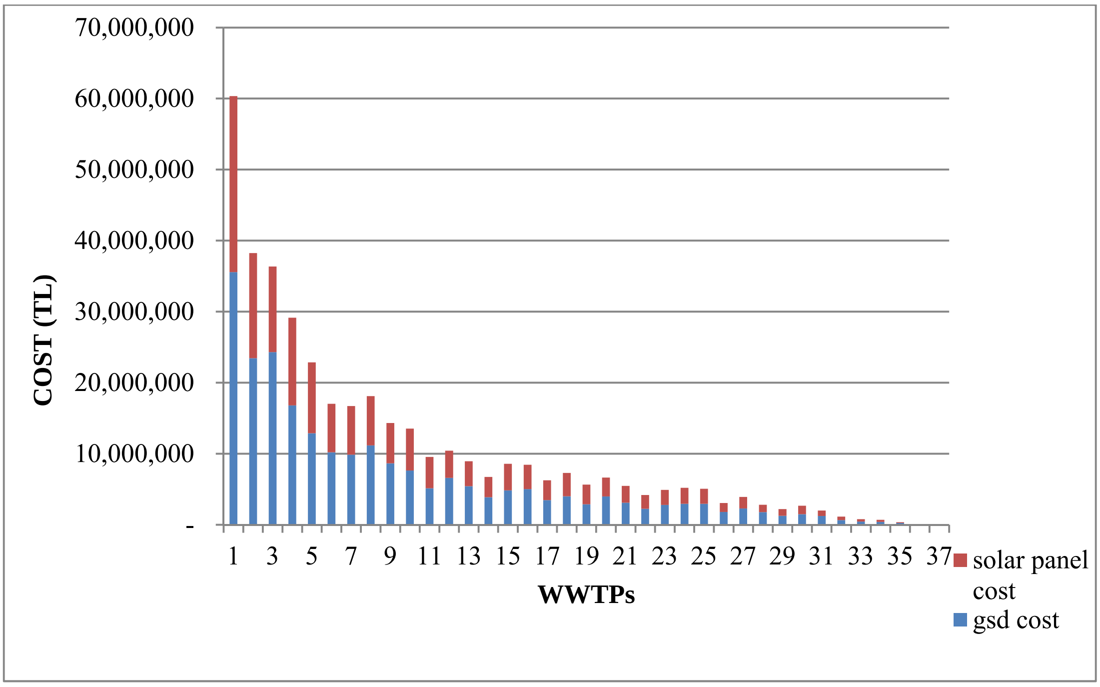


Figure 4.2 GSD and solar panel cost distribution

Figure 4.3 shows cost per kg of evaporated water in an hour for each WWTP. The results indicated that the lowest cost per unit of water evaporated was observed for AK-5 WWTP whereas the highest cost was found to be for KAR-1 WWTP, which also has the least sludge production. The average cost per evaporated water was found to be 3,679 TL / evaporated water (kg/hr). Figure 4.4 shows GSD area per evaporated water amount for each WWTP with an average of 3.07 GSD Area/ evaporated water (kg/hr). The smallest GSD area was observed for AK-8 WWTP and the highest GSD area was for İÇ-4 WWTP. The overall GSD area results showed that while the WWTPs in Mediterranean Region require an area below the average requirement, the WWTPs in Marmara Region (except MAR-15, MAR-3) and central Anatolian region need more space for GSD. WWTPs in Marmara region are generally close to city centers. Therefore, available area can be a limitation to construct a GSD. Therefore, required area for Marmara region can be critical for feasibility of a GSD. WWTPs in Central Anatolia have are associated with high flow rates. As a result, produced sludge amounts require large areas for drying.

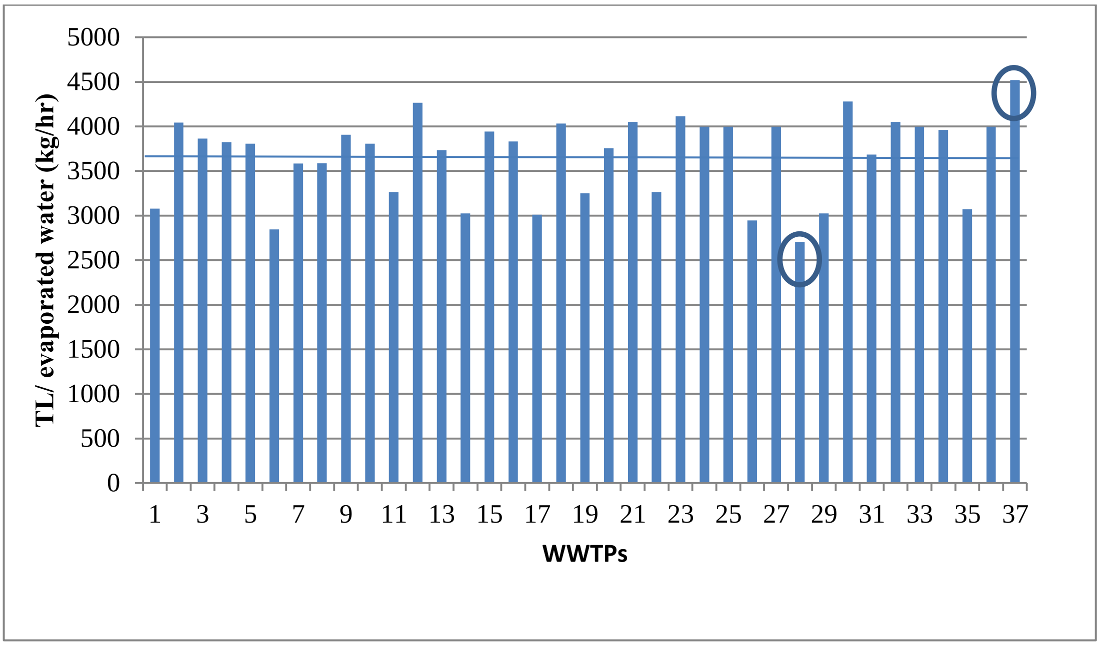


Figure 4.3 Installation cost of WWTPs in terms of evaporated water amount (*The horizontal line shows the average)*

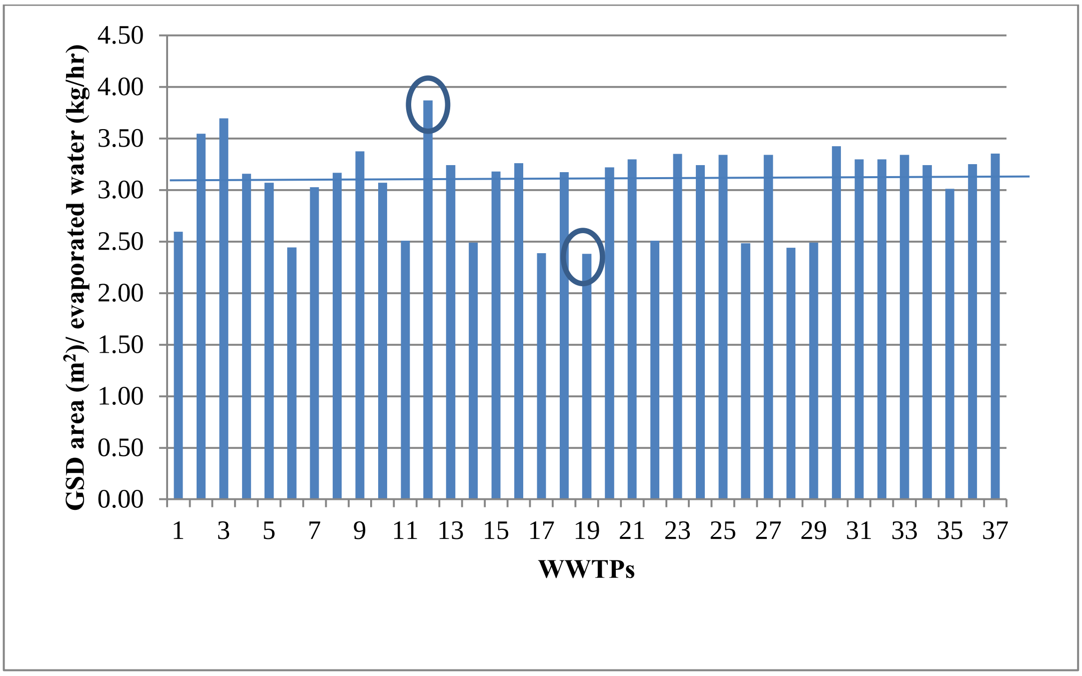


Figure 4.4 GSD area of WWTPs in terms of evaporated water amount (*The horizontal line shows the average)*

The required installation costs and GSD areas were determined for a target dry matter content of 90% DS and illustrated in Figure 4.5 and Figure 4.6, respectively. The average value of cost and GSD area per dried sludge amount is 11,709 TL/dry sludge (kg/hr) and 9.80 m^2/ dry sludge (kg/hr), respectively. Because the initial dry matter and sludge production rate of WWTPs are different than each other, a trend between results was not observed. However, cost per dry matter content and GSD area per dry matter content showed the importance of dewatering. MAR-15 WWTP, whose cost and GSD area per dry matter content is the highest, has the lowest initial dry solids content (2% DS). This value is disregarded in calculation of the average value due to extremely low DSi value which is an outlier compared to the DSi values for other WWTPs. The second high cost and GSD area per dry matter ratio belonged to KAR-1 WWTP which has sludge production of 10kg/hr and DS_i of 15%DS. The lowest cost and GSD area per dry matter ratio belonged to MAR-8 WWTP whose sludge production rate is the lowest in this study (4kg/hr) with a very high DS_i (40%DS). Because of the conflicting results obtained from the examples illustrated above we concluded that not the sludge production rate but DSi is a decisive parameter to determine the ratio of cost per dry matter content and GSD area per dry matter content.

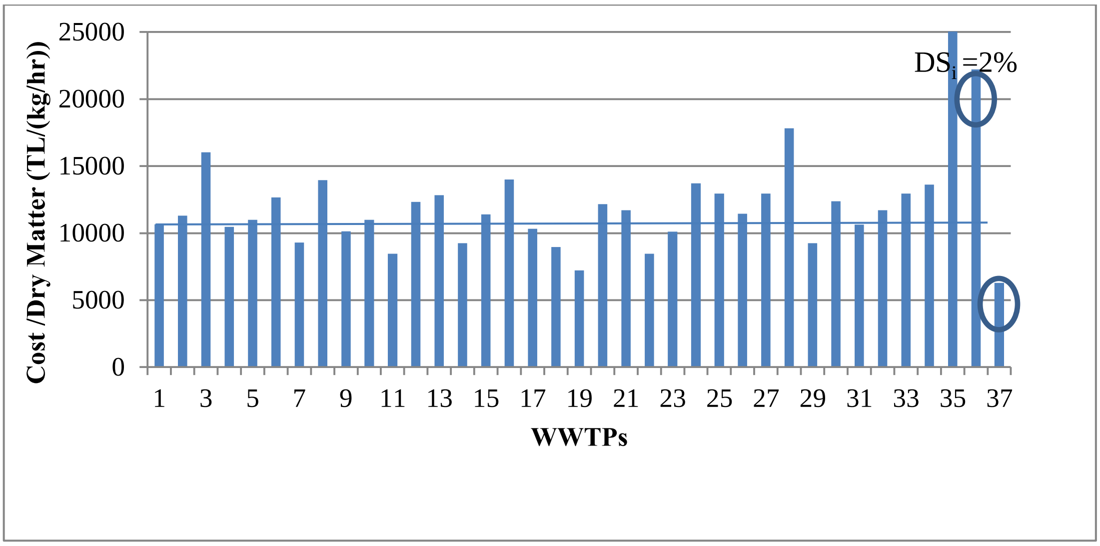


Figure 4.5 Installation cost of WWTPs in terms of dry sludge amount (*The horizontal line shows the average, (without added highest data))*

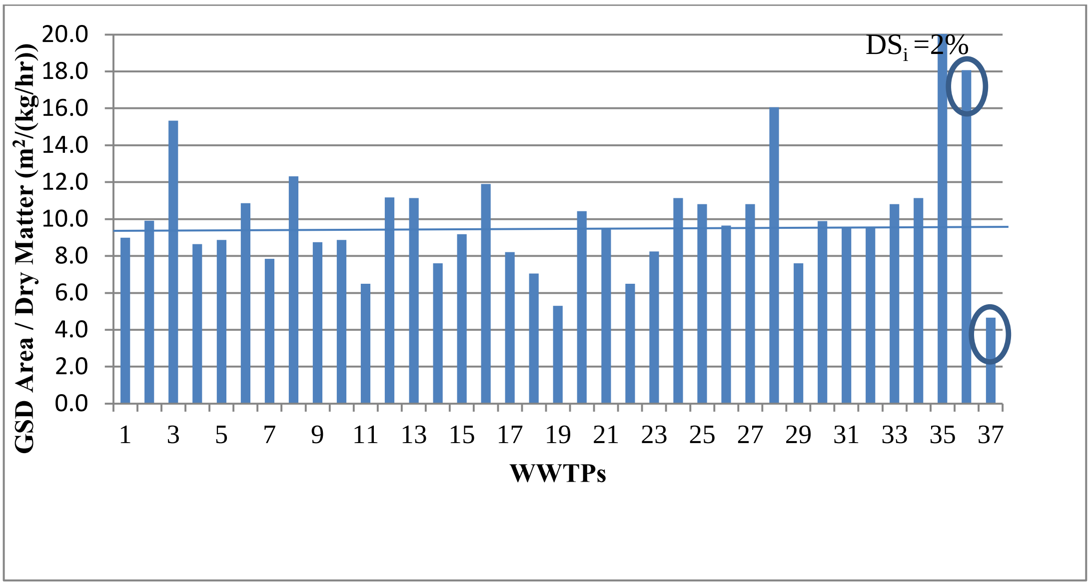


Figure 4.6 GSD area of WWTPs in terms of dry sludge amount (*The horizontal line shows the average (without added highest data))*

The constraint on different upper limits for the DS attainable at the greenhouse solar dryer (i.e.60%, 50% and 40 %,) revealed that this constraint is a binding constraint. As a result, in all solutions the resource associated with this constraint (DS_m) is fully used. Therefore, in all WWTPs the optimal DS_m values were the same for a given upper limit on DS_m. Changes in cost and area values are shown in Figure 4.7, Figure 4.8 and Figure 4.9 for EGE-1, MAR-8, and AK-5, respectively.EGE-1 WWTP had the highest flow rate, MAR-8 WWTP had one of the lowest flow rates and AK-5 WWTP had average flow rates compared to other WWTPs in Turkey. Results for the other WWTPs are provided in Appendix-C.

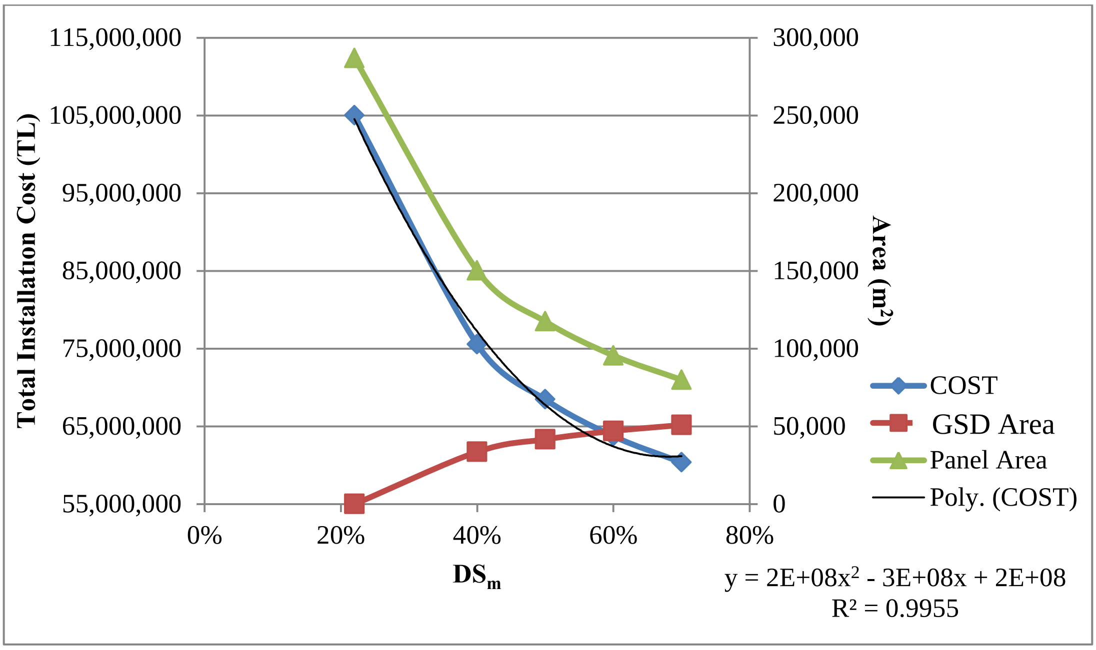


Figure 4.7 EGE-1 WWTP (DS_i = 0.22; sludge production = 25,901 kg/hr)

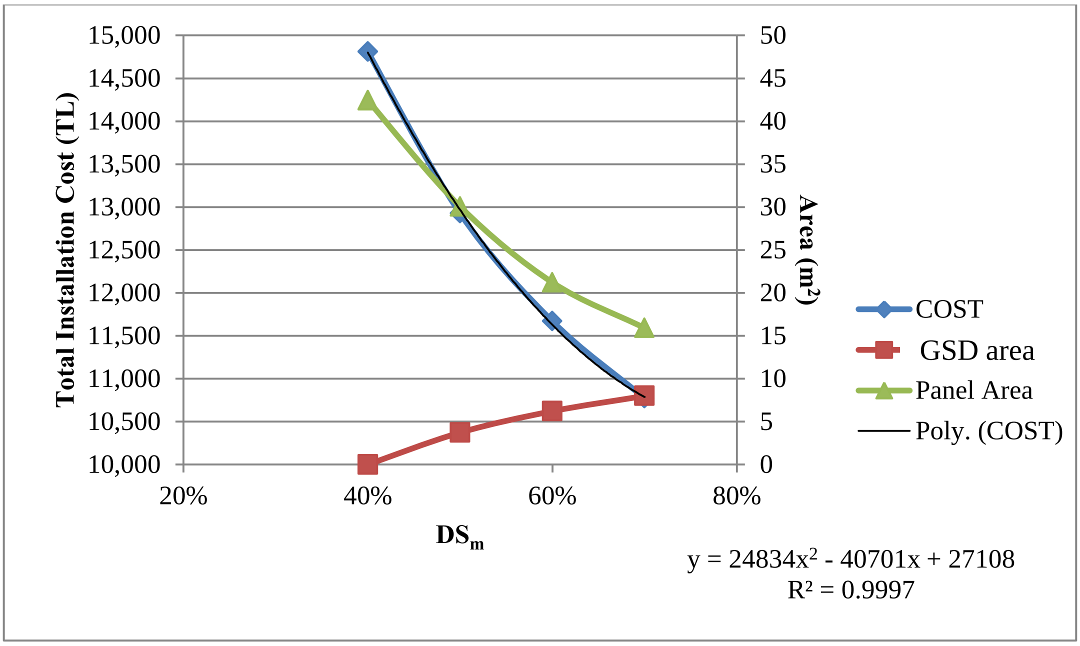


Figure 4.8 MAR-8 WWTP (DS_i = 0.40; sludge production = 4 kg/hr)

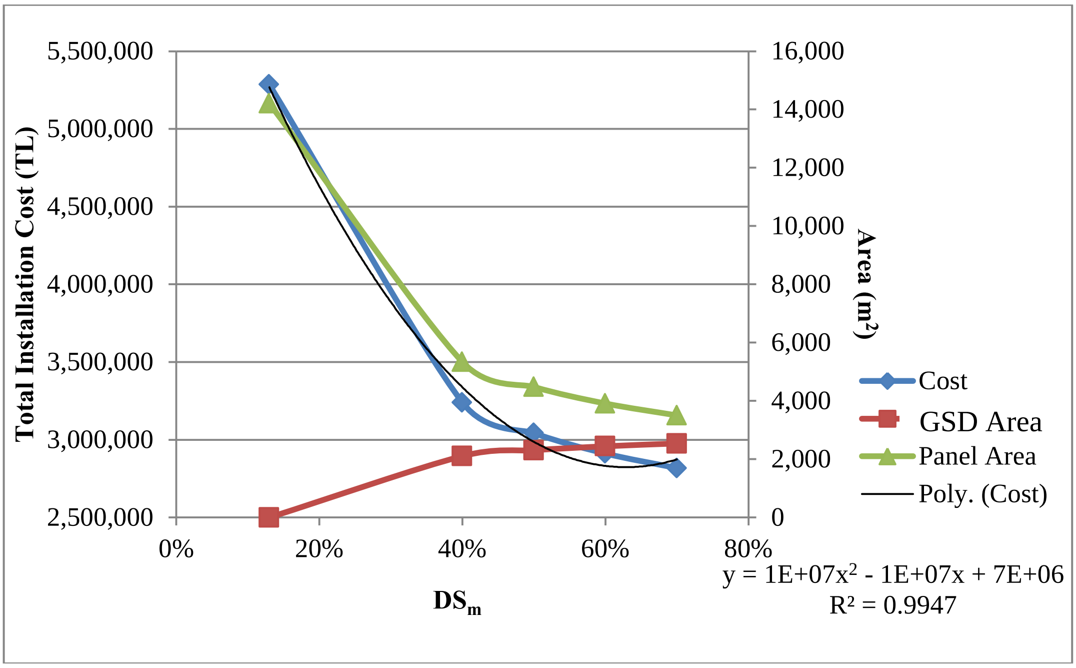
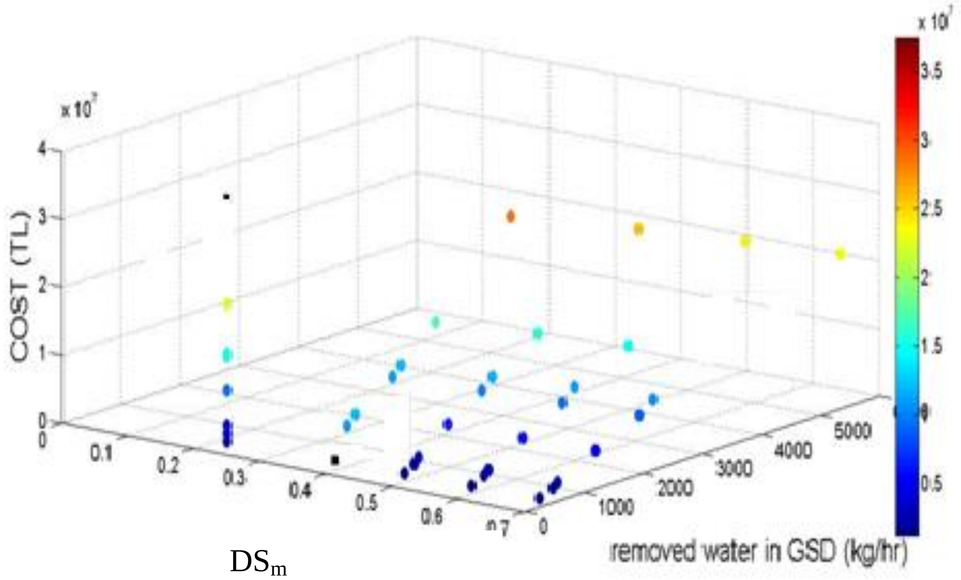


Figure 4.9 AK-5 WWTP (DS_i = 0.13; sludge production = 1217 kg/hr)

For all 37 WWTPs, similar trends were observed so that DS_i and sludge production rate did not affect DS_m value, cost and area distribution trend. Increase in DS_m leads to an increase of sludge drying area of the greenhouse and decrease in the solar panel area to reach 90% DS. Moreover, the overall total area is used for drying and the cost decrease. In other words, solar panel cost of the system has a significant impact on total cost compared to greenhouse solar dryer installation cost. As a result, smaller solar panel areas lead to reduction in total cost in the first year of installation. As shown in Figure 4.7 to Figure 4.9, relationships between DS_m and costs were presented by second order polynomial equations. As mentioned in Chapter 2, while sludge dries, the water amount remaining in sludge shows parabolic distribution as given in Figure 2.5. The results of cost functions depending on DS_m have similar parabolic distribution with Figure 2.5. Hence, reliability of calculated functions increases.

The aim of the optimization model is to determine the optimum final water percentage in the greenhouse solar dryer (DS_m) in order to minimize the costs of sludge drying to 90% DS. The optimal costs of drying with respect to different upper limits for the constraint on attainable DS_m and the amount of removed water from the sludge in greenhouse solar dryer are also demonstrated in Figure 4.10. This figure illustrates that the higher the removed water from sludge is, the higher the installation cost for GSD will be. However, the same figure also indicates that when removed water amount is kept constant, installation cost increases with the decrease in final sludge dryness (DS_m). This result concludes that the amount of removed water is the indicative parameter instead of DS_m for our study.



x-axis: Removed water in GSD, y-axis: DS_m, z-axis: Total cost (solar panel and GSD)

Figure 4.10 Distribution of optimal costs in relation to DS_m and amount of removed water in GSD

Another critical issue in the optimization problem was the constraint on area requirement. The assumption in this study was that the area available for drying for each WWTP could not be more than the total facility area (including land without construction) estimated from Google Earth view. Sludge area was determined based on the DS_f aimed to be achieved in GSD (ex. 50 %, 60 % and 70 %). The additional energy required to dry the sludge up to 90 % of DS was obtained from solar dryers that did not have any additional effect on the area requirement because of their flexibility in placement. Table 4.1 shows WWTP area estimates, GSD area and solar panel area requirement determined for DS_m of 70%. Table 4.2 and 4.3 summarize similar information for DS_m of 60%, and 50%, respectively.

Table 4. 1 Areas and costs for DS_m of 70%

WWTP	WWTP Area (m^2)	DS_m = 70 %			COST (TL)
		GSD Area (m^2)	Solar Panel Area (m^2)	Total drying area (m^2)	
EGE-1	232,314	50,902	79,957	130,860	60,359,216
İÇ-1	454,834	33,548	47,752	81,299	38,245,286
İÇ-2	135,556	34,767	39,776	74,543	36,360,183
MAR-10	185,574	24,052	39,847	63,899	29,141,172
MAR-9	172,339	18,446	32,550	50,997	22,867,910
AK-4	179,134	14,615	22,351	36,966	17,026,373
GÜN-1	63,580	14,124	21,697	35,821	16,724,485
MAR-3	276,000	15,992	22,892	38,884	18,116,092
İÇ-3	139,588	12,378	18,093	30,471	14,322,687
MAR-11	125,751	10,921	19,272	30,194	13,539,223
AK-1	151,178	7,338	14,095	21,433	9,560,219
İÇ-4	41,123	9,453	12,352	21,805	10,420,867
MAR-5	44,715	7,762	11,544	19,306	8,944,521
AK-3	20,527	5,540	9,084	14,624	6,729,343
MAR-21	34,846	6,924	12,278	19,201	8,587,067
MAR-16	90,139	7,186	11,355	18,541	8,444,302
AK-9	20,570	4,975	9,064	14,039	6,268,792
MAR-2	140,910	5,750	10,496	16,246	7,306,117
AK-8	116,470	4,136	8,622	12,758	5,645,655
MAR-4	63,543	5,693	8,693	14,387	6,639,775
MAR-14	24,172	4,465	7,762	12,226	5,486,458
AK-2	91,200	3,209	6,164	9,373	4,181,187
MAR-20	35,081	3,992	6,811	10,802	4,901,747
MAR-19	17,748	4,227	7,523	11,750	5,210,392
MAR-12	37,050	4,234	6,959	11,193	5,066,397
AK-7	30,096	2,586	4,104	6,690	3,067,883
MAR-17	43,771	3,277	5,388	8,665	3,921,901
AK-5	20,100	2,540	3,503	6,044	2,817,916
AK-6	52,736	1,814	2,975	4,789	2,203,346
MAR-7	26,866	2,145	3,917	6,062	2,683,100
MAR-1	77,250	1,786	2,383	4,168	1,995,755
MAR-13	16,575	936	1,628	2,564	1,150,763
MAR-18	19,116	654	1,075	1,729	782,857
MAR-6	14,185	575	1,002	1,577	703,055
MAR-15	35,143	363	419	782	370,205
KAR-1	2,161	27	49	76	32,938
MAR-8	35,033	8	16	24	10,772

Table 4.2 Areas and costs for DS_m of 60%

WWTP	WWTP Area (m^2)	DSm = 60 %			COST (TL)
		GSD Area (m^2)	Solar Panel Area (m^2)	Total drying area (m^2)	
EGE-1	232,314	47,053	95,602	142,655	63,735,223
İÇ-1	454,834	30,324	58,225	88,549	39,926,085
İÇ-2	135,556	32,608	46,530	79,139	37,414,874
MAR-10	185,574	21,684	49,316	71,000	30,955,475
MAR-9	172,339	16,738	39,458	56,196	24,220,726
AK-4	179,134	13,771	25,791	39,563	17,802,911
GÜN-1	63,580	12,646	26,890	39,536	17,680,626
MAR-3	276,000	14,926	27,339	42,265	18,997,751
İÇ-3	139,588	11,083	22,065	33,148	14,950,297
MAR-11	125,751	9,910	23,362	33,272	14,340,174
AK-1	151,178	6,570	17,363	23,933	10,273,878
İÇ-4	41,123	8,578	15,120	23,698	10,833,453
MAR-5	44,715	7,169	13,915	21,084	9,398,659
AK-3	20,527	5,059	10,961	16,019	7,136,248
MAR-21	34,846	6,282	15,037	21,319	9,131,657
MAR-16	90,139	6,673	13,789	20,462	8,942,051
AK-9	20,570	4,595	10,699	15,294	6,641,905
MAR-2	140,910	5,032	13,245	18,276	7,812,784
AK-8	116,470	3,619	10,747	14,366	6,112,518
MAR-4	63,543	5,229	10,551	15,780	6,995,438
MAR-14	24,172	4,051	9,639	13,690	5,858,940
AK-2	91,200	2,873	7,594	10,467	4,493,307
MAR-20	35,081	3,548	8,803	12,351	5,289,787
MAR-19	17,748	3,904	9,004	12,908	5,509,746
MAR-12	37,050	3,888	8,527	12,415	5,377,505
AK-7	30,096	2,413	4,783	7,196	3,217,980
MAR-17	43,771	3,010	6,600	9,610	4,162,731
AK-5	20,100	2,444	3,912	6,356	2,911,704
AK-6	52,736	1,656	3,588	5,245	2,336,577
MAR-7	26,866	1,947	4,734	6,680	2,836,287
MAR-1	77,250	1,620	2,993	4,613	2,106,224
MAR-13	16,575	850	2,022	2,872	1,228,890
MAR-18	19,116	601	1,317	1,918	830,929
MAR-6	14,185	531	1,200	1,731	742,887
MAR-15	35,143	361	428	789	372,465
KAR-1	2,161	26	57	82	34,398
MAR-8	35,033	6	21	27	11,669

Table 4.3 Areas and costs for DS_m of 50%

WWTP	WWTP Area (m^2)	DSm = 50 %			COST (TL)
		GSD Area (m^2)	Solar Panel Area (m^2)	Total drying area (m^2)	
EGE-1	232,314	41,663	117,507	159,169	68,461,631
İÇ-1	454,834	25,811	72,887	98,698	42,279,204
İÇ-2	135,556	29,586	55,987	85,573	38,891,441
MAR-10	185,574	18,367	62,571	80,939	33,495,499
MAR-9	172,339	14,347	49,129	63,476	26,114,669
AK-4	179,134	12,591	30,606	43,197	18,890,065
GÜN-1	63,580	10,576	34,162	44,739	19,019,224
MAR-3	276,000	13,433	33,567	47,000	20,232,073
İÇ-3	139,588	9,269	27,626	36,895	15,828,951
MAR-11	125,751	8,494	29,088	37,582	15,461,506
AK-1	151,178	5,495	21,938	27,433	11,273,001
İÇ-4	41,123	7,353	18,996	26,349	11,411,074
MAR-5	44,715	6,339	17,232	23,571	10,034,451
AK-3	20,527	4,384	13,591	17,975	7,705,915
MAR-21	34,846	5,385	18,899	24,284	9,894,084
MAR-16	90,139	5,954	17,195	23,149	9,638,899
AK-9	20,570	4,063	12,988	17,051	7,164,264
MAR-2	140,910	4,025	17,091	21,116	8,522,117
AK-8	116,470	2,895	13,724	16,619	6,766,128
MAR-4	63,543	4,579	13,149	17,728	7,493,367
MAR-14	24,172	3,473	12,265	15,738	6,380,414
AK-2	91,200	2,403	9,595	11,998	4,930,276
MAR-20	35,081	2,927	11,592	14,519	5,833,044
MAR-19	17,748	3,452	11,076	14,528	5,928,841
MAR-12	37,050	3,405	10,720	14,125	5,813,058
AK-7	30,096	2,172	5,736	7,908	3,428,116
MAR-17	43,771	2,636	8,299	10,935	4,499,892
AK-5	20,100	2,309	4,481	6,790	3,043,007
AK-6	52,736	1,435	4,449	5,885	2,523,099
MAR-7	26,866	1,669	5,877	7,546	3,050,748
MAR-1	77,250	1,389	3,846	5,235	2,260,881
MAR-13	16,575	728	2,572	3,300	1,338,267
MAR-18	19,116	526	1,656	2,182	898,230
MAR-6	14,185	470	1,478	1,947	798,651
MAR-15	35,143	359	442	800	375,628
KAR-1	2,161	24	65	89	36,443
MAR-8	35,033	4	30	34	12,925

The table concludes an invert relationship between DS_m value and GSD area. For example, on average sludge drying area consists of 38 % of the total area (GSD area + Solar Panel) when DS_m is 70 %. This value is 20 % of total area on average for all WWTPs when DS_m is 50 %. Solar panels cover larger area than GSD area to reach 90 % in all WWTPs. Moreover, while DS_m ratio decreases from 70%DS to 50%DS, required GSD area decreases approximately up to 24%.

The relationships between sludge production rate, GSD area and solar panel area for 70 %DS_m in greenhouse solar dryer is illustrated in Figure 4.7. Extrapolation performed with Matlab programming resulted in the 3D surface plotted in Figure 4.11. The green points show the data points and colorful label is the extrapolated surface for 37 WWTPs.The extrapolation was not very accurate because the data points used were too close to each other. Therefore, interpolation was essential to analyze the results and the data was interpolated in Matlab programming with "interpl" comment.

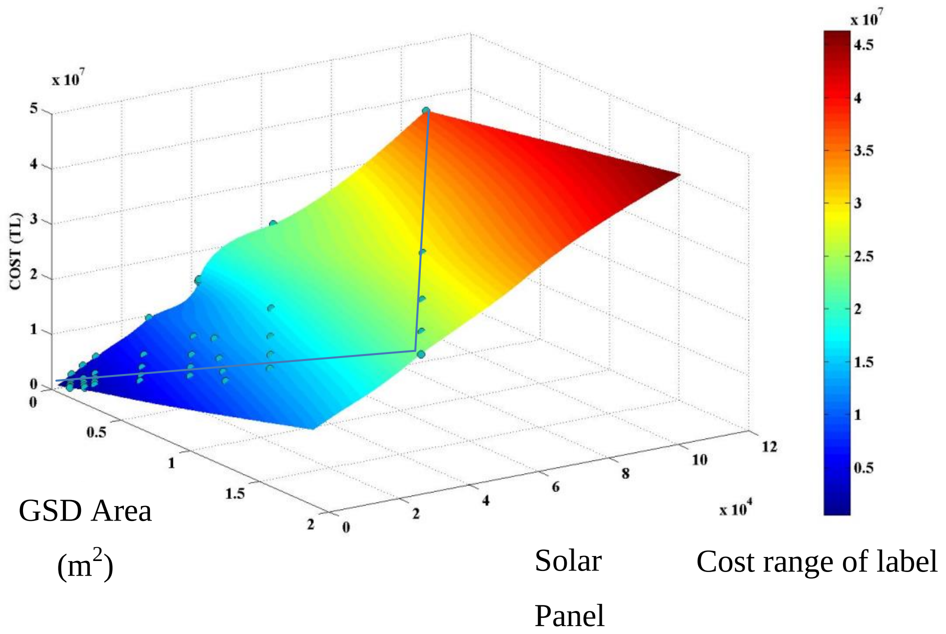


Figure 4.11 3D surface plot of cost, GSD and solar panel areas for 37 WWTPs

In Figure 4.11, the triangular surface shows interpolation regression of the data (area between dots). Thus the error within the triangle surface is less than the extrapolation area because limit area occurs of existing data. For the triangular area shown in Figure 4.11, the relationship between cost, GSD and solar panel area determined by Matlab for the assumptions used in this study is given as (with 95% confidence interval).

$$COST(TL) = (629 * GSDarea) + (349.2 * panelarea) - 23230 \quad \textbf{(4. 1)}$$

When the results obtained by Equation 4.1 were compared with the results obtained through optimization, the regression constant between both data sets was 0.80. However, when two data points of small WWTPs were excluded from the system, the regression constant increased to 0.93. Therefore, Equation 4.1 can be useful for middle and high flow rate sludge producing WWTPs to get rough cost values for greenhouse solar driers supported with solar panel system for the assumptions used in this study.

4.1.2. Results of D90C2

If a WWTP has enough area for sludge drying using conventional drying beds, it can also have sufficient area for GSD area or solar panels, as shown in Figure 4.12. However, in Turkey, the land reserved for WWTPs especially in the regions near settlements and industry can be limited (see Marmara Region). Also, regions that do not have large flat areas, as in Blacksea Region and Mediterranean Region, are limited to build WWTPs and drying units. Hence, area constraint for a GSD can be an important parameter that needs to be evaluated.

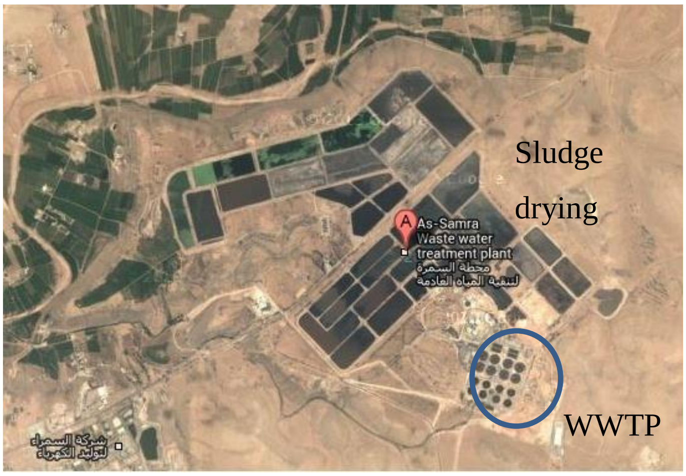


Figure 4.12 As-SemraWWTP in Jordan (Google map)

Because the largest greenhouse solar dryer area in the world is the Palma de Mallorca greenhouse solar drying plant in Spain with an area of 20,000 m² (Ritterbusch et.al., 2012),in this scenario the area constraint was chosen to be less than or equal to20,000 m^2 as well. Optimization function and the decision variables were kept constant with scenario D90C1.

Compared to scenario D90C1 the results of scenario D90C2 were identical except for the WWTPs with the highest load. Optimization result of rest of the WWTPs gave same result of D90C1, because they require less than 20,000 m^2 to reach 70 % DS. The results of scenario D90C2 is given on Table 4.4.

Table 4.4 Results of optimization with sludge area constraint 20,000 m^2

WWTP name	Sludge production (kg/h)	DSi (%)	DS_m (%)	Cost (TL)	GSD Area (m^2)	Solar Panel Area (m^2)
EGE-1	25,901	22	0.30	85,128,235	20,000	131,958
İÇ-1	13,223	26	0.41	42,978,633	20,000	50,681
İÇ-2	11,930	19	0.33	41,244,888	20,000	49,624
MAR-10	10,714	26	0.54	32,244,991	20,000	56,045

The results showed that DS_m value decreases and does not reach the upper limit value due to area limitation and that the greenhouse solar dryer cannot dry wet sludge till 70% DS. Moreover, solar panel requirement increases to fill the gap. Increase in solar panels increases the installation cost, because unit cost of the solar panel is more expensive than the unit cost of greenhouse solar dryer. The cost increase in this scenario compared to D90C1 is 41%, 12%, 13% and 11% for EGE-1, İÇ-1, İÇ-2 and MAR-10 WWTPs, respectively. Furthermore, solar panel requirement increases by 34% in average in this scenario compared to D90C1 to compensate for more water evaporation need. As a result, this scenario concluded that use of greenhouse solar drying system may not be feasible for WWTPs with high sludge production rates.

4.1.3. Results of D90C3

The assumption of the scenario D90C3 is that wet sludge is dried until 70%DS in greenhouse solar dryer and remaining water in sludge is evaporated by auxiliary heat from solar panels. This scenario used the GSD area constraint to be less or equal to 5% of the WWTP area. The results are provided in Table 4.5.

Table 4.5 Results of scenario D90C3

WWTP	DS_i	Sludge Production Rate (kg/hr)	DS_m	5% of WWTP Area (m^2)	Calculated GSD Area (m^2)	Calculated Panel Area (m^2)	Cost (TL)	Indica-tor (*)
EGE-1	0.22	25,901	0.26	11,616	11,616	239,614	94,810,611	Red
İÇ-1	0.26	13,223	0.45	22,742	22,742	82,858	43,879,199	Yellow
İÇ-2	0.19	11,930	0.22	6,778	6,778	76,565	49,087,535	Red
MAR-10	0.26	10,714	0.34	9,279	9,279	98,899	40,456,616	Red
MAR-9	0.25	8,321	0.36	8,617	8,617	72,304	30,653,256	Red
AK-4	0.18	7,476	0.29	8,957	8,957	30,219	23,900,449	Red
GÜN-1	0.27	6,668	0.31	3,179	3,179	37,641	24,028,750	Red
MAR-3	0.20	6,493	0.52	13,800	13,800	32,036	19,928,885	Green
İÇ-3	0.27	5,239	0.41	6,979	6,979	20,941	17,074,679	Yellow
MAR-11	0.25	4,927	0.40	6,288	6,288	38,012	17,209,439	Red
AK-1	0.27	4,181	0.70	7,559	7,400	14,095	9,560,219	Blue
İÇ-4	0.25	3,382	0.29	2,056	2,056	35,750	13,907,614	Red
MAR-5	0.22	3,170	0.27	2,236	2,236	33,634	13,177,195	Red
AK-3	0.24	3,035	0.27	1,026	1,026	26,677	10,541,890	Red
MAR-21	0.25	3,016	0.30	1,742	1,742	16,988	11,061,560	Red
MAR-16	0.21	2,874	0.35	4,507	4,507	10,521	9,281,247	Red
AK-9	0.22	2,757	0.26	1,029	1,029	16,939	10,532,660	Red
MAR-2	0.30	2,717	0.70	7,046	5,811	10,496	7,306,117	Blue
AK-8	0.30	2,606	0.70	5,824	4,136	8,622	5,645,655	Blue
MAR-4	0.23	2,374	0.37	3,177	3,177	18,752	8,567,087	Red
MAR-14	0.25	1,875	0.30	1,209	1,209	22,542	8,420,309	Red
AK-2	0.27	1,829	0.70	4,560	3,236	6,164	4,181,187	Blue
MAR-20	0.28	1,730	0.38	1,754	1,754	16,863	6,859,518	Red
MAR-19	0.22	1,726	0.25	887	887	10,496	6,700,181	Red
MAR-12	0.23	1,702	0.32	1,853	1,853	8,002	5,940,979	Red
AK-7	0.20	1,339	0.34	1,505	1,505	8,368	4,009,018	Red
MAR-17	0.23	1,318	0.41	2,189	2,189	4,477	4,141,650	Yellow
AK-5	0.13	1,217	0.19	1,005	1,005	9,976	4,309,168	Red
AK-6	0.24	994	0.70	2,637	1,916	2,975	2,203,346	Blue
MAR-7	0.25	868	0.42	1,343	1,343	7,215	3,301,581	Yellow
MAR-1	0.25	750	0.70	3,863	1,773	2,383	1,995,755	Blue
MAR-13	0.25	393	0.70	829	829	1,628	1,150,763	Blue
MAR-18	0.23	263	0.70	956	654	1,075	782,857	Blue
MAR-6	0.22	235	0.70	709	584	1,002	703,055	Blue
MAR-15	0.02	123	0.70	35,143	359	419	370,205	Blue
KAR-1	0.15	10	0.70	108	27	49	32,938	Blue
MAR-8	0.40	4	0.70	1,751	8	16	10,772	Blue

**BLUE: 60% DS<$DS_m \leq$ 70%DS, GREEN: 50% DS <$DS_m \leq$ 60%DS, YELLOW: 40% DS <$DS_m \leq$ 50%DS, RED: $DS_m \leq$ 40%DS*

The results of the optimization concluded that in WWTPs marked in blue, it was possible to reach 70% DS within the given area constraints. Only in 12 of the 37 WWTPs it was possible to use GSD to reach a DS_m greater than 60%. The average sludge production rate of WWTPs marked in blue was 50 kg/d (1175 kg/hr). Those WWTPs were located generally at Marmara and Mediterranean regions. Additionally in KAR-1 it was possible to reach greater than 60 % DS with the GSD. Sludge production rates of WWTPs in Marmara Region and KAR-1 were mainly low (average of 30 kg/d), on the other hand WWTPs in Mediterranean Region were higher (average of 174 kg/d). The WWTPs indicated in green needed a little more investment and the WWTPs in yellow required evaluation of other methods or needed more GSD area to reduce cost and increase the DS_m value. The WWTPs marked in red were resource-intensive, because the sludge could be dried only up to 25-35% DS with dewatering process (McFarland, 2000; Chen et al., 2012). The average sludge production rates of WWTPs marked in red was 222 kg/d. These WWTPs had generally high sludge production rates such as EGE-1. The overall results from this optimization mainly resulted in either blue or red colored situations. Especially Marmara Region and Mediterranean Region were sensitive locations because all the resource-intensive scenarios were observed from those areas (10 from Marmara and 5 from Mediterranean Regions). The WWTPs in Marmara and Mediterranean Region have limited area, because WWTPs in Marmara region are located close to cities, the WWTPS in Mediterranean Region are located in mountain region.

4.1.4. Results of D90C4

The scenario D90C4 relaxed the constraint on the area limitation for GSD compared to D90C3. An area corresponding to 10% of the WWTP area was assumed to be available for GSD. The results are summarized in Table 4.6.

Table 4.6 Results of scenario D90C4

WWTP	DS_i	Sludge Production Rate (kg/hr)	DS_m	10% of WWTP Area (m^2)	Calculated GSD Area (m^2)	Calculated Panel Area (m^2)	Cost (TL)	Indica-tor (*)
EGE-1	0.22	25,901	0.32	23,231	23,231	192,409	84,624,560	
İÇ-1	0.26	13,223	0.70	45,483	33,548	47,752	38,245,286	
İÇ-2	0.19	11,930	0.25	13,556	13,556	62,755	45,914,467	
MAR-10	0.26	10,714	0.43	18,557	18,557	30,571	30,862,971	
MAR-9	0.25	8,321	0.54	17,234	17,234	17,209	22,217,581	
AK-4	0.18	7,476	0.70	17,913	17,478	22,351	17,026,373	
GÜN-1	0.27	6,668	0.37	6,358	6,358	48,984	21,748,040	
MAR-3	0.20	6,493	0.70	27,600	15,992	22,892	18,116,092	
İÇ-3	0.27	5,239	0.70	13,959	12,378	18,093	14,322,687	
MAR-11	0.25	4,927	0.70	12,575	10,921	19,272	13,539,223	
AK-1	0.27	4,181	0.70	15,118	7,400	14,095	9,560,219	
İÇ-4	0.25	3,382	0.35	4,112	4,112	15,797	12,048,879	
MAR-5	0.22	3,170	0.36	4,472	4,472	24,697	11,464,799	
AK-3	0.24	3,035	0.32	2,053	2,053	226,768	9,675,030	
MAR-21	0.25	3,016	0.37	3,485	3,485	12,942	9,960,119	
MAR-16	0.21	2,874	0.70	9,014	7,186	11,355	8,444,302	
AK-9	0.22	2,757	0.31	2,057	2,057	13,819	9,466,844	
MAR-2	0.30	2,717	0.70	14,091	5,811	10,496	7,306,117	
AK-8	0.30	2,606	0.70	11,647	4,136	8,622	5,645,655	
MAR-4	0.23	2,374	0.70	6,354	5,694	8,693	6,639,775	
MAR-14	0.25	1,875	0.38	2,417	2,417	7,581	6,098,570	
AK-2	0.27	1,829	0.70	9,120	3,236	6,164	4,181,187	
MAR-20	0.28	1,730	0.49	3,508	3,508	3,733	4,642,214	
MAR-19	0.22	1,726	0.31	1,775	1,775	8,437	6,139,188	
MAR-12	0.23	1,702	0.50	3,705	3,705	3,788	4,818,311	
AK-7	0.20	1,339	0.70	3,010	2,586	4,104	3,067,883	
MAR-17	0.23	1,318	0.70	4,377	3,277	5,388	3,921,901	
AK-5	0.13	1,217	0.37	2,010	2,010	5,739	3,333,082	
AK-6	0.24	994	0.70	5,274	1,916	2,975	2,203,346	
MAR-7	0.25	868	0.70	2,687	2,145	3,917	2,683,100	
MAR-1	0.25	750	0.70	7,725	1,773	2,383	1,995,755	
MAR-13	0.25	393	0.70	1,658	829	1,628	1,150,763	
MAR-18	0.23	263	0.70	1,912	654	1,075	782,857	
MAR-6	0.22	235	0.70	1,419	584	1,002	703,055	
MAR-15	0.02	123	0.70	3514,3	359	419	370,205	
KAR-1	0.15	10	0.70	216	27	49	32,938	
MAR-8	0.40	4	0.70	3,503	8	16	10,772	

**BLUE: 60% DS<$DS_m \leq$ 70%DS, GREEN: 50% DS <$DS_m \leq$ 60%DS, YELLOW: 40% DS <$DS_m \leq$ 50%DS, RED: $DS_m \leq$ 40%DS*

The color-coding was kept the same as for D90C3. Results summarized that when constraint area was increased by an additional 5 %, the DS_m values were improved. The average sludge production rate of WWTPs marked in blue is 114 kg/d. These WWTPs marked in blue included the lowest sludge production rates which are KAR-1 and MAR-8. 11 WWTP did not have enough area for the GSD to dry the sludge to higher than 40%DS. Among those WWTPs 4 of them were located in Marmara Region and 3 of them in the Mediterranean Region. This scenario showed that WWTPs in Marmara region, generally, may need very large areas to dry their wet sludge using solar energy.

4.2. Evaluating Thermal Dryer Use

Thermal dryer is the most well-known technology to dry sludge to high DS content. It may neither be cheap nor environmental friendly due to CO_2 emissions during fossil or other fuel combustion. Nevertheless, for WWTPs whose area is limited or in case of a requirement by regulations this technology which can provide 90% DS can be used. Although the construction and even the energy cost for the first year operation can be comparable with solar dryer systems, required energy cost at long term (such as 28 years, assumed from TUBITAK KAMAG project) can be very high for thermal dryers.

The project TUBITAK KAMAG 108G167 suggested that the 37 WWTPs in Turkey considered in this study should use thermal drying. Figure 4.13 shows previously determined short term (1 year) and long-term (years between 2012-2040) energy and construction costs.

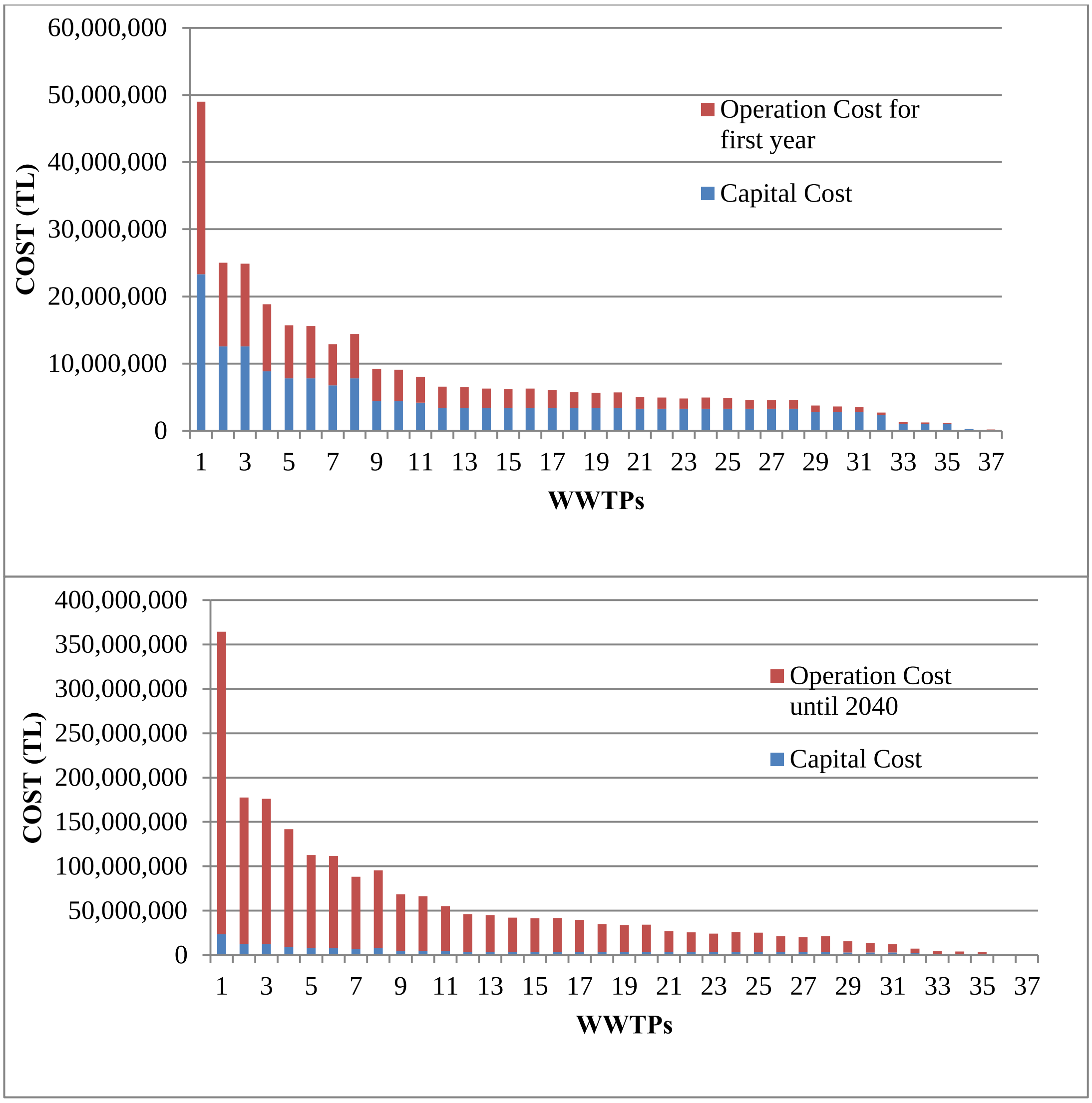


Figure 4.13 Short term (1 year) and long term (28 years) energy and construction costs for thermal dryers without co-generation

Figure 4.13 demonstrates the sum of operation and installation cost of conventional thermal drying (with no co-generation) at given WWTPs. The total cost for the operation and installation for thermal driers in long term will be high due to energy costs. In the first year, mainly installation cost will be dominant especially for relatively smaller WWTPs. That means that while large WWTPs are enforced to use thermal drying in order to reach 90 % DS, they are also forced to utilize more energy. The average energy consumption for 37 WWTPs corresponds to 36% of the total cost on average for the first year. However, this value increases up to 84% in the long term. Total construction and energy cost of thermal dryer changes between 49 million to 156,000 TL for the first year, 364 million to 195,000 TL for the long term.

A thermal drying unit with co-generation is developed to decrease the energy consumption or increase energy production by using co-generation systems. Although its first investment cost is expensive, it is more desirable to use in long term. TUBİTAK-KAMAG (108G167) project it was assumed that natural gas was used to startup the operation. Figure 4.14 shows results for 37 WWTPs.

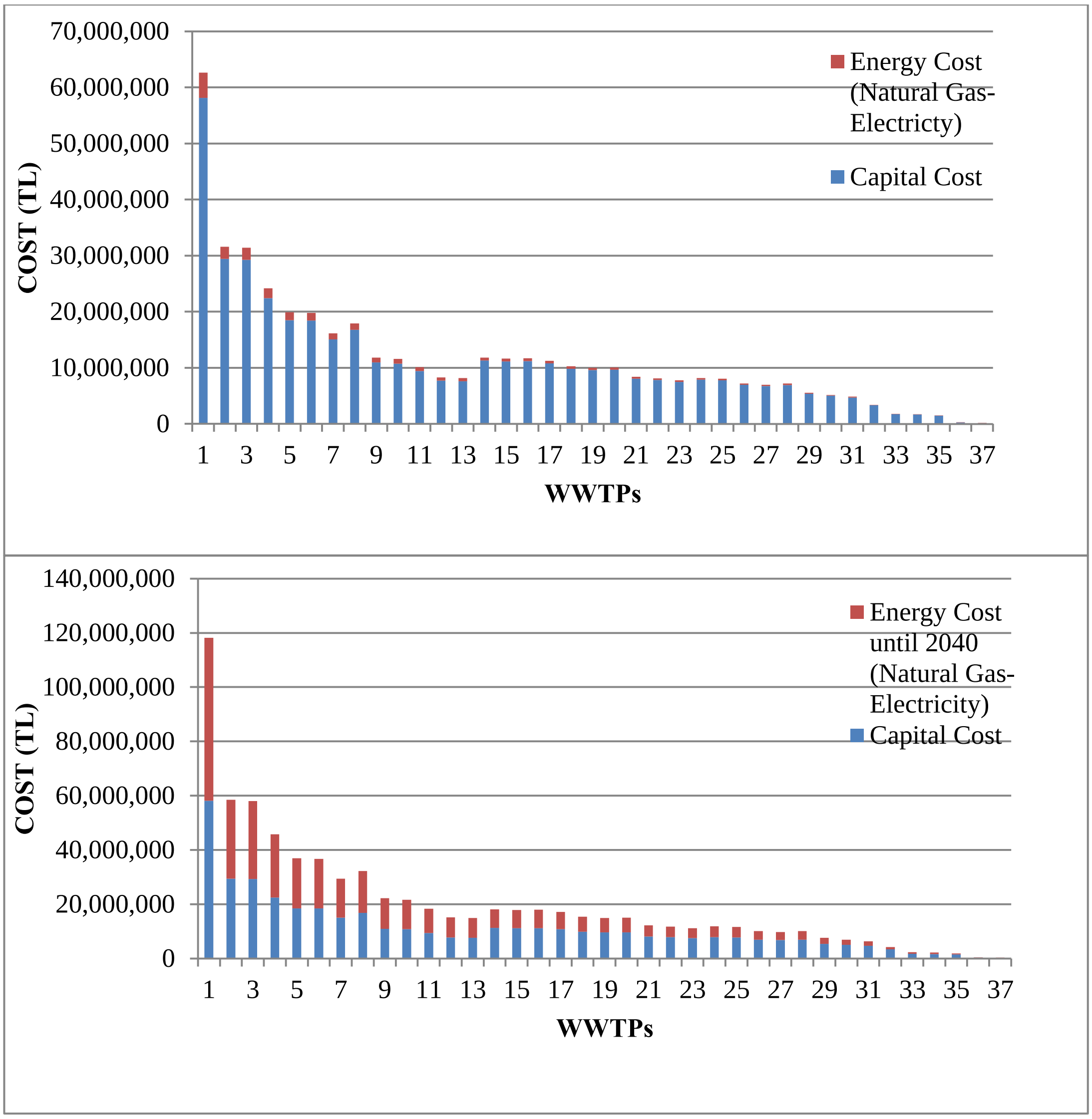


Figure 4.14 Short term (1 year) and long term (28 years) energy and construction costs for thermal dryers with co-generation

Co-generation thermal dryer system construction cost changes between 58 million to 162,000 TL. Required energy for the system was calculated for natural gas. The energy cost for the first year changes between 4.5 million to 558 TL. The same value for long term changes between 60 million to 7,400 TL. While energy cost of the system consisted of 4% of the total cost for the first year in average, this value would change to 37% of the total cost up to 2040. The Figure 4.14 obviously showed that even though co-generation investment cost is higher, energy consumption is very low when both conventional and co-generation thermal dryer costs are compared.

These two thermal drying approaches were also compared with GSD including solar panels considering the same constraints as in D90C1. Comparisons are based on example small, large and average WWTPs classified by their sludge production rates. Figure 4.15 shows cost distribution of the largest WWTP (EGE-1). For this WWTP, although the investment cost of thermal dryer device is cheaper than GSD with solar panel, energy requirement of conventional thermal dryer makes it resource-intensive. The investment cost of cogeneration and GSD with solar panel is similar. GSD with solar panel does not require any additional energy because all energy requirements including ventilation and mixing is obtained from solar panel which is produced daily.

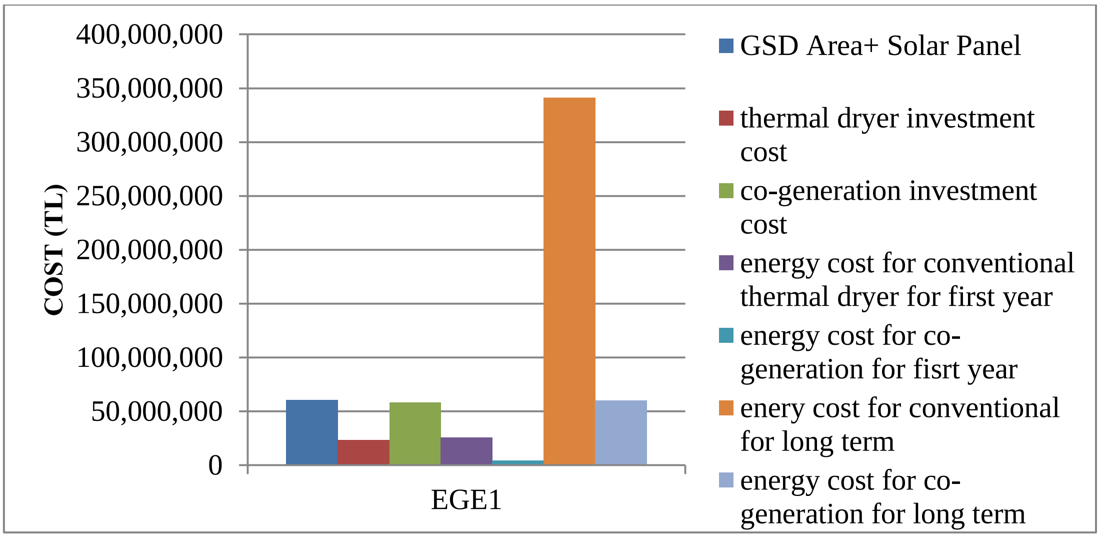


Figure 4.15 Investments and energy requirement cost of scenarios (EGE-1)

Figure 4.16 and Figure 4.17 show the cost comparisons of different drying alternatives for average and small flow rate WWTPs, respectively. The results showed that GSD with solar panel is the most economical option to dry sludge to 90% DS. Yet, GSD with solar panel for the largest WWTP is still controversial. Although the total cost of GSD with solar panel is cheaper than thermal dryer options, this system is covered large areas both GSD area and solar panel area. Therefore, it is undesirable option for operator in WWTP. Furthermore, there is not any example in the literature which has GSD area larger than 20,000 m^2. However, GSD with solar panel option should be considered for average and small WWTPs in terms of cost and energy requirement. This system has both cheaper investment cost and no need for additional energy cost. Also, required area covers less than 20,000 m^2, which is feasible in regard to existing GSD dryer unit (Ritterbusch et al., 2012).

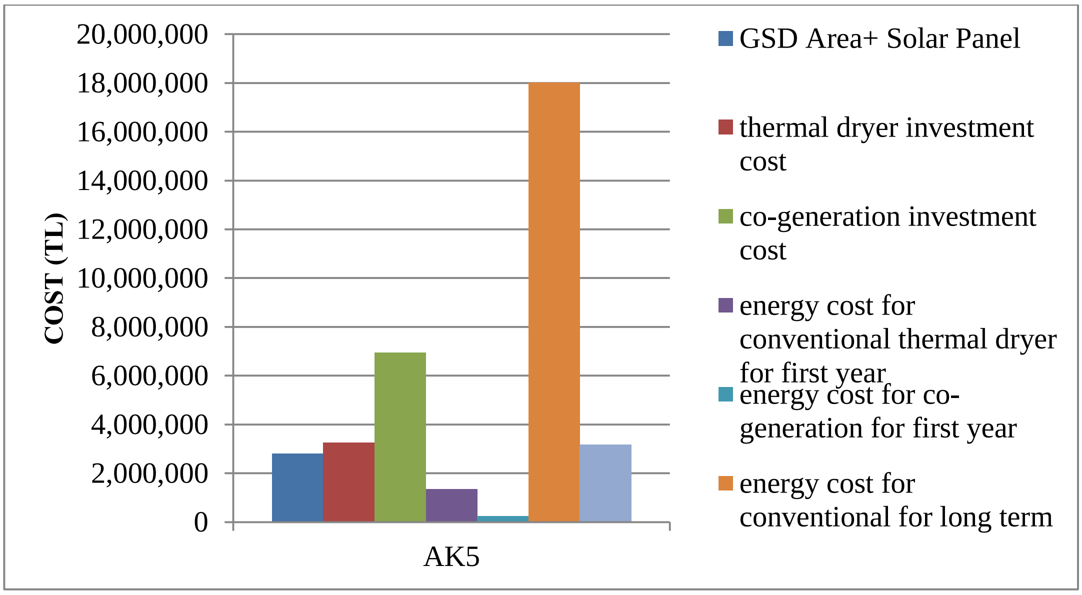


Figure 4.16 Investments and energy requirement cost of scenarios (AK-5)

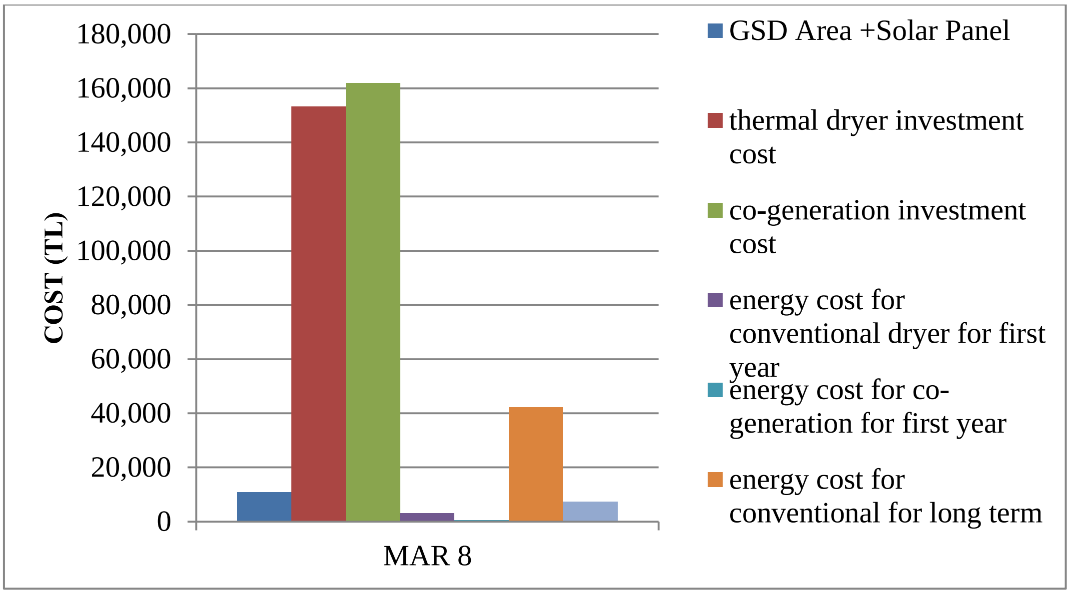


Figure 4.17 Investments and energy requirement cost of scenarios (MAR-8)

4.3.1. Evaluating Solar Panel System in GSD by Using Only Solar Duration Time

In previous section, solar panels were compared with thermal dryer system. For the comparison GSD supported with solar panel systems and just using solar panel systems were assumed to work non-stop every day. Nevertheless, as mentioned in Chapter-2, while sludge is drying in the GSD supported with solar panels, it can be incubated up to 2-3 days. In this scenario, the energy required during nighttime was ignored. The energy was obtained from the solar panels during daytime and results in DS_m of 70 % DS. Based on all those assumptions Table 4.7 shows solar duration time, required solar panel area, GSD area, total area and total installation costs.

Table 4.7 Areas and costs for DS_m of 70 % with solar panel work only solar duration

WWTP	Solar duration time (hr)	GSD Area (m^2)	Solar Panel Area (m^2)	Total Drying Area (m^2)	Cost (TL)
EGE-1	7.90	50,902	10,254	60,600	41,884,324
İÇ-1	7.00	33,548	6,116	39,221	26,995,091
İÇ-2	7.30	34,767	4,141	39,387	27,418,203
MAR-10	6.50	24,052	5,039	28,695	19,696,571
MAR-9	6.50	18,446	3,769	22,437	15,431,140
AK-4	8.40	14,615	2,453	17,227	12,003,734
GÜN-1	7.60	14,124	3,240	17,357	11,894,054
MAR-3	6.50	15,992	2,376	18,568	12,889,552
İÇ-3	7.60	12,378	2,547	15,028	10,316,496
MAR-11	6.50	10,921	2,231	13,279	9,133,223
AK-1	7.50	7,338	2,033	9,432	6,442,984
İÇ-4	6.70	9,453	1,531	10,974	7,568,568
MAR-5	6.50	7,762	1,271	8,974	6,207,431
AK-3	8.40	5,540	1,313	6,864	4,721,804
MAR-21	6.00	6,924	1,368	8,368	5,755,831
MAR-16	5.60	7,186	1,108	8,346	5,780,230
AK-9	7.90	4,975	1,099	6,068	4,189,335
MAR-2	6.50	5,750	1,467	7,278	4,959,355
AK-8	7.90	4,136	1,402	5,535	3,749,781
MAR-4	6.50	5,693	993	6,685	4,615,868
MAR-14	5.60	4,465	852	5,316	3,657,208
AK-2	7.50	3,209	889	4,125	2,817,856
MAR-20	5.60	3,992	877	4,798	3,281,649
MAR-19	5.60	4,227	695	4,985	3,446,969
MAR-12	5.60	4,234	716	4,889	3,373,881
AK-7	8.40	2,586	486	3,071	2,131,184
MAR-17	5.60	3,277	553	3,783	2,611,724
AK-5	8.40	2,540	293	2,819	1,984,672
AK-6	8.40	1,814	430	2,247	1,546,030
MAR-7	5.70	2,145	394	2,580	1,776,178
MAR-1	7.00	1,786	339	2,113	1,454,301
MAR-13	5.60	936	179	1,115	767,085
MAR-18	5.60	654	111	756	521,435
MAR-6	5.70	575	94	677	468,984
MAR-15	5.60	363	7	366	260,999
KAR-1	4.80	27	4	31	20,817
MAR-8	6.70	8	4	11	7,313

Use of solar panels during solar duration would require more time to dry sludge but it will be cheaper and it will cover less area compare to scenario D90C1. The area required for solar panel decreases by 88 % while total cost of the drying system decreases by 31 % when solar panels are used during solar duration. This result indicates that if 20 % of the already dedicated GSD area is increased for solar panels, GSD drying units can dry the sludge up to 90 % DS. Wherefore this system doesn't work quickly like thermal dryers or D90C1 scenario, sludge storage tank could be used during operation. Therefore, GSD systems supported with or without solar panels should be considered for intermediate and low flow rate WWTPs.

4.3.2. Evaluation of Maintenance and Operation Costs

Operation and maintenance costs of a GSD are cheaper than thermal dryer systems as mentioned in Chapter 2. Operation cost of thermal dryers with and without co-generation systems is calculated as the required energy cost. Maintenance cost of thermal dryer with and without co-generation systems are taken from the TUBİTAK-KAMAG project. In TUBİTAK-KAMAG study, annual maintenance cost was 1% of the investment cost. Maintenance and operation costs of a GSD supported with solar panels are separately calculated for the GSD and the solar panel. Maintenance and operation costs for a GSD are assumed 1 % of the investment cost (TUBİTAK-KAMAG, 2013). This value for solar panel is assumed as 3% of the investment cost of the solar panels (EPR, 2010). Costs are provided in Table 4.8, Table 4.9 and Table 4.10 for GSD supported with solar panels and thermal dryers with and without cogeneration, respectively. Total operation and maintenance cost of a conventional thermal dryers is the highest due to energy requirement. Although co-generation thermal dryer maintenance cost is higher than for the conventional one due to high level equipment, operation cost is cheaper because of less energy requirement. It is obvious that the total operation and maintenance cost for GSD with solar panel is the cheapest, due to low equipment and energy requirements.

Table 4.8 Operation and Maintenance Cost for GSD supported with solar panels

WWTP	GSD			SP			GSD+ SP			TOTAL (1year)	TOTAL (28 years)
	Construction cost	O&M cost		Construction cost	O&M cost		Construction cost	O&M cost			
		1year	28 years		1year	28 years		1year	28 years		
EGE-1	35,580,498	355,805	4,724,263	24,778,718	743,362	9,870,112	60,359,216	1,099,167	14,594,375	61,458,383	74,953,591
İÇ-1	23,450,052	234,501	3,113,621	14,795,234	443,857	5,893,389	38,245,286	678,358	9,007,010	38,923,644	47,252,296
İÇ-2	24,302,133	243,021	3,226,758	12,058,050	361,742	4,803,086	36,360,183	604,763	8,029,844	36,964,946	44,390,027
MAR-10	16,812,348	168,123	2,232,289	12,328,824	369,865	4,910,943	29,141,172	537,988	7,143,232	29,679,160	36,284,404
MAR-9	12,893,754	128,938	1,711,991	9,974,156	299,225	3,973,008	22,867,910	428,162	5,684,998	23,296,072	28,552,908
AK-4	10,215,885	102,159	1,356,432	6,810,488	204,315	2,712,823	17,026,373	306,473	4,069,255	17,332,846	21,095,628
GÜN-1	9,872,676	98,727	1,310,862	6,851,809	205,554	2,729,283	16,724,485	304,281	4,040,144	17,028,766	20,764,629
MAR-3	11,178,408	111,784	1,484,233	6,937,684	208,131	2,763,489	18,116,092	319,915	4,247,722	18,436,007	22,363,814
İÇ-3	8,652,222	86,522	1,148,814	5,670,465	170,114	2,258,718	14,322,687	256,636	3,407,531	14,579,323	17,730,218
MAR-11	7,633,779	76,338	1,013,588	5,905,444	177,163	2,352,317	13,539,223	253,501	3,365,905	13,792,724	16,905,128
AK-1	5,129,262	51,293	681,047	4,430,957	132,929	1,764,984	9,560,219	184,221	2,446,031	9,744,440	12,006,250
İÇ-4	6,607,647	66,076	877,342	3,813,220	114,397	1,518,921	10,420,867	180,473	2,396,263	10,601,340	12,817,130
MAR-05	5,425,638	54,256	720,399	3,518,883	105,566	1,401,677	8,944,521	159,823	2,122,076	9,104,344	11,066,597
AK-3	3,872,460	38,725	514,173	2,856,883	85,706	1,137,983	6,729,343	124,431	1,652,155	6,853,774	8,381,498
MAR-21	4,839,876	48,399	642,623	3,747,191	112,416	1,492,619	8,587,067	160,814	2,135,242	8,747,881	10,722,309
MAR-16	5,023,014	50,230	666,939	3,421,288	102,639	1,362,802	8,444,302	152,869	2,029,742	8,597,171	10,474,044
AK-9	3,477,525	34,775	461,734	2,791,267	83,738	1,111,846	6,268,792	118,513	1,573,580	6,387,305	7,842,372
MAR-2	4,019,250	40,193	533,663	3,286,867	98,606	1,309,258	7,306,117	138,799	1,842,921	7,444,916	9,149,038
AK-8	2,891,064	28,911	383,866	2,754,591	82,638	1,097,237	5,645,655	111,548	1,481,103	5,757,203	7,126,758
MAR-4	3,979,407	39,794	528,373	2,660,368	79,811	1,059,705	6,639,775	119,605	1,588,078	6,759,380	8,227,853
MAR-14	3,121,035	31,210	414,401	2,365,423	70,963	942,219	5,486,458	102,173	1,356,620	5,588,631	6,843,078
AK-2	2,243,091	22,431	297,830	1,938,096	58,143	772,002	4,181,187	80,574	1,069,833	4,261,761	5,251,020
MAR-20	2,790,408	27,904	370,501	2,111,339	63,340	841,010	4,901,747	91,244	1,211,511	4,992,991	6,113,258
MAR-19	2,954,673	29,547	392,312	2,255,719	67,672	898,521	5,210,392	97,218	1,290,833	5,307,610	6,501,225
MAR-12	2,959,566	29,596	392,962	2,106,831	63,205	839,214	5,066,397	92,801	1,232,176	5,159,198	6,298,573
AK-7	1,807,614	18,076	240,009	1,260,269	37,808	502,003	3,067,883	55,884	742,012	3,123,767	3,809,895
MAR-17	2,290,623	22,906	304,141	1,631,278	48,938	649,787	3,921,901	71,845	953,929	3,993,746	4,875,830
AK-5	1,775,460	17,755	235,740	1,042,456	31,274	415,242	2,817,916	49,028	650,982	2,866,944	3,468,898
AK-6	1,267,986	12,680	168,359	935,360	28,061	372,582	2,203,346	40,741	540,941	2,244,087	2,744,287
MAR-7	1,499,355	14,994	199,079	1,183,745	35,512	471,521	2,683,100	50,506	670,601	2,733,606	3,353,701

Table 4.8 Operation and Maintenance Cost for GSD supported with solar panels (cont'd)

WWTP	GSD			SP			GSD+SP			1year	28 years
	Construction cost	O & M cost		Construction cost	O & M cost		Construction cost	O & M cost			
		1year	28 years		1year	28 years		1year	28 years		
MAR-1	1,248,414	12,484	165,760	747,341	22,420	297,689	1,995,755	34,904	463,449	2,030,659	2,459,204
MAR-13	654,264	6,543	86,871	496,499	14,895	197,771	1,150,763	21,438	284,642	1,172,201	1,435,405
MAR-18	457,146	4,571	60,698	325,711	9,771	129,741	782,857	14,343	190,439	797,200	973,296
MAR-6	401,925	4,019	53,366	301,130	9,034	119,949	703,055	13,053	173,315	716,108	876,370
MAR-15	253,737	2,537	33,690	116,468	3,494	46,393	370,205	6,031	80,083	376,236	450,288
KAR-1	18,873	189	2,506	14,065	422	5,603	32,938	611	8,108	33,549	41,046
MAR-8	5,592	56	742	5,180	155	2,063	10,772	211	2,806	10,983	13,578

Table 4.9 Required Operation and Maintenance Cost for Conventional Thermal Dryers

WWTP	Conventional Thermal Dryers					Total Cost (CC+O&M)	
	Construction Cost	Maintenance Cost		Operation Cost		1 years	28 years
		1 years	28 years	1 year	28 years		
EGE-1	23,300,000	233,000	3,093,698	25,691,569	341,124,274	49,224,569	367,517,972
İÇ-1	12,582,000	125,820	1,670,597	12,422,890	164,947,085	25,130,710	179,199,682
İÇ-2	12,582,000	125,820	1,670,597	12,308,842	163,432,795	25,016,662	177,685,392
MAR-10	8,854,000	88,540	1,175,605	10,006,365	132,861,254	18,948,905	142,890,859
MAR-9	7,805,500	78,055	1,036,389	7,887,844	104,732,221	15,771,399	113,574,109
AK-4	7,805,500	78,055	1,036,389	7,817,898	103,803,500	15,701,453	112,645,389
GÜN-1	6,757,000	67,570	897,172	6,133,983	81,445,024	12,958,553	89,099,196
MAR-3	7,805,500	78,055	1,036,389	6,608,301	87,742,867	14,491,856	96,584,755
İÇ-3	4,427,000	44,270	587,803	4,819,684	63,994,194	9,290,954	69,008,996
MAR-11	4,427,000	44,270	587,803	4,670,093	62,007,978	9,141,363	67,022,781
AK-1	4,194,000	41,940	556,866	3,846,338	51,070,422	8,082,278	55,821,287
İÇ-4	3,378,500	33,785	448,586	3,206,015	42,568,428	6,618,300	46,395,514
MAR-05	3,378,500	33,785	448,586	3,137,284	41,655,836	6,549,569	45,482,922
AK-3	3,378,500	33,785	448,586	2,919,457	38,763,596	6,331,742	42,590,682
MAR-21	3,378,500	33,785	448,586	2,858,494	37,954,156	6,270,779	41,781,242
MAR-16	3,378,500	33,785	448,586	2,885,358	38,310,847	6,297,643	42,137,933
AK-9	3,378,500	33,785	448,586	2,728,917	36,233,677	6,141,202	40,060,763
MAR-2	3,378,500	33,785	448,586	2,385,673	31,676,193	5,797,958	35,503,279
AK-8	3,378,500	33,785	448,586	2,287,721	30,375,616	5,700,006	34,202,703
MAR-4	3,378,500	33,785	448,586	2,316,992	30,764,260	5,729,277	34,591,346
MAR-14	3,262,000	32,620	433,118	1,777,531	23,601,482	5,072,151	27,296,600
AK-2	3,262,000	32,620	433,118	1,682,206	22,335,782	4,976,826	26,030,900
MAR-20	3,262,000	32,620	433,118	1,567,138	20,807,948	4,861,758	24,503,066

Table 4.9 Required Operation and Maintenance Cost for Conventional Thermal Dryers (cont'd)

WWTP	Conventional Thermal Dryers					Total Cost (CC+O&M)	
	Construction Cost	Maintenance Cost		Operation Cost		1 years	28 years
		1 years	28 years	1 years	28 years		
MAR-19	3,262,000	32,620	433,118	1,708,427	22,683,932	5,003,047	26,379,050
MAR-12	3,262,000	32,620	433,118	1,661,341	22,058,748	4,955,961	25,753,866
AK-7	3,262,000	32,620	433,118	1,363,176	18,099,804	4,657,796	21,794,922
MAR-17	3,262,000	32,620	433,118	1,286,045	17,075,692	4,580,665	20,770,810
AK-5	3,262,000	32,620	433,118	1,357,416	18,023,324	4,652,036	21,718,442
AK-6	2,796,000	27,960	371,244	955,899	12,692,119	3,779,859	15,859,363
MAR-7	2,796,000	27,960	371,244	822,450	10,920,226	3,646,410	14,087,470
MAR-1	2,796,000	27,960	371,244	710,920	9,439,359	3,534,880	12,606,603
MAR-13	2,330,000	23,300	309,370	372,830	4,950,318	2,726,130	7,589,688
MAR-18	1,021,880	10,219	135,682	256,709	3,408,504	1,288,808	4,566,066
MAR-6	1,021,880	10,219	135,682	232,443	3,086,304	1,264,542	4,243,866
MAR-15	1,021,880	10,219	135,682	156,437	2,077,122	1,188,536	3,234,684
KAR-1	241,343	2,413	32,045	10,757	142,829	254,514	416,217
MAR-8	153,242	1,532	20,347	3,167	42,052	157,942	215,641

Table 4.10 Required Operation and Maintenance Cost for Co-generation Thermal Dryers

WWTP	Co-generation Thermal Dryers					Total Cost (CC+O&M)	
	Construction Cost	Maintenance Cost		Operation Cost		1 years	28 years
		1 years	28 years	1 year	28 years		
EGE-1	58,141,990	2,081,017	27,631,066	4,522,142	60,043,525	64,745,149	145,816,582
İÇ-1	29,429,481	1,006,254	13,360,714	2,186,635	29,033,420	32,622,370	71,823,615
İÇ-2	29,274,813	997,016	13,238,056	2,166,560	28,766,880	32,438,390	71,279,750
MAR-10	22,424,276	810,516	10,761,762	1,761,286	23,385,782	24,996,078	56,571,820
MAR-9	18,502,713	638,915	8,483,310	1,388,391	18,434,606	20,530,020	45,420,629
AK-4	18,407,855	633,250	8,408,084	1,376,080	18,271,136	20,417,184	45,087,074
GÜN-1	15,075,689	496,853	6,597,047	1,079,683	14,335,674	16,652,224	36,008,410
MAR-3	16,767,442	535,272	7,107,172	1,163,170	15,444,199	18,465,885	39,318,813
İÇ-3	10,963,284	390,394	5,183,530	848,344	11,264,039	12,202,022	27,410,852
MAR-11	10,760,414	378,278	5,022,646	822,014	10,914,432	11,960,706	26,697,492
AK-1	9,410,267	311,553	4,136,704	677,019	8,989,241	10,398,839	22,536,211
İÇ-4	7,726,384	259,687	3,448,043	564,312	7,492,749	8,550,383	18,667,175
MAR-05	7,633,173	254,120	3,374,123	552,214	7,332,117	8,439,507	18,339,413
AK-3	11,297,027	236,476	3,139,851	513,873	6,823,035	12,047,375	21,259,913
MAR-21	11,131,676	231,538	3,074,287	503,142	6,680,560	11,866,357	20,886,523
MAR-16	11,204,540	233,714	3,103,179	507,871	6,743,344	11,946,125	21,051,063
AK-9	10,780,221	221,042	2,934,928	480,335	6,377,728	11,481,598	20,092,877
MAR-2	9,849,230	193,240	2,565,772	419,918	5,575,535	10,462,388	17,990,537
AK-8	9,583,552	185,305	2,460,425	402,677	5,346,612	10,171,534	17,390,589
MAR-4	9,662,943	187,676	2,491,905	407,829	5,415,019	10,258,448	17,569,868
MAR-14	8,083,249	143,980	1,911,720	312,875	4,154,252	8,540,104	14,149,221
AK-2	7,824,696	136,259	1,809,198	296,096	3,931,468	8,257,050	13,565,362
MAR-20	7,512,594	126,938	1,685,444	275,842	3,662,544	7,915,374	12,860,581
MAR-19	7,895,815	138,383	1,837,398	300,711	3,992,748	8,334,909	13,725,961

Table 4.10 Required Operation and Maintenance Cost for Co-generation Thermal Dryers (cont'd)

WWTP	Co-generation Thermal Dryers					Total Cost (CC+O&M)	
	Construction Cost	Maintenance Cost		Operation Cost		1 years	28 years
		1 years	28 years	1 year	28 years		
MAR-12	7,768,104	134,569	1,786,759	292,424	3,882,705	8,195,096	13,437,568
AK-7	6,959,381	110,417	1,466,084	239,942	3,185,865	7,309,740	11,611,331
MAR-17	6,750,178	104,170	1,383,131	226,365	3,005,605	7,080,713	11,138,914
AK-5	6,943,758	109,951	1,459,889	238,928	3,172,404	7,292,636	11,576,051
AK-6	5,388,713	77,428	1,028,062	168,254	2,234,023	5,634,395	8,650,798
MAR-7	5,026,755	66,618	884,538	144,765	1,922,141	5,238,139	7,833,434
MAR-1	4,724,248	57,584	764,588	125,134	1,661,484	4,906,966	7,150,320
MAR-13	3,341,238	30,199	400,976	65,624	871,338	3,437,062	4,613,552
MAR-18	1,718,160	20,793	276,089	45,185	599,953	1,784,139	2,594,203
MAR-6	1,652,342	18,828	249,991	40,914	543,241	1,712,084	2,445,573
MAR-15	1,446,189	12,671	168,247	27,536	365,608	1,486,396	1,980,044
KAR-1	270,520	871	11,569	1,893	25,140	273,284	307,229
MAR-8	161,832	257	3,406	557	7,402	162,646	172,640

4.4. Overall Evaluation

The main aim of this part of the study was to evaluate whether GSD supported with solar panels could be more economical than thermal dryer to obtain 90% dry sludge in selected WWTPs. The results of the optimization runs showed that while DS_m value is at maximum (70% DS), the greenhouse solar dryer with solar panel is the cheapest option to dry sludge. Therefore, the cost of GSD supported with solar panels was compared with thermal dryers at this DS_m value.

The costs are compared to costs for conventional and co-generation thermal driers. The comparisons were made for short-term (1 year) and long-term (28 years) use. Although thermal dryer requires continuous energy source, which would change the cost of the system, greenhouse solar dryer and solar panels produce and consume energy daily. So, energy cost of greenhouse solar dryer and solar panels are the same at short and long terms, because solar panels produce energy daily and this energy is consumed throughout the day. Therefore, long term energy requirement estimation is not needed. In summary for all options, Figure 4.18 showed comparisons of the different sludge drying techniques in short-term and Figure 4.19 showed the same comparison in long-term.

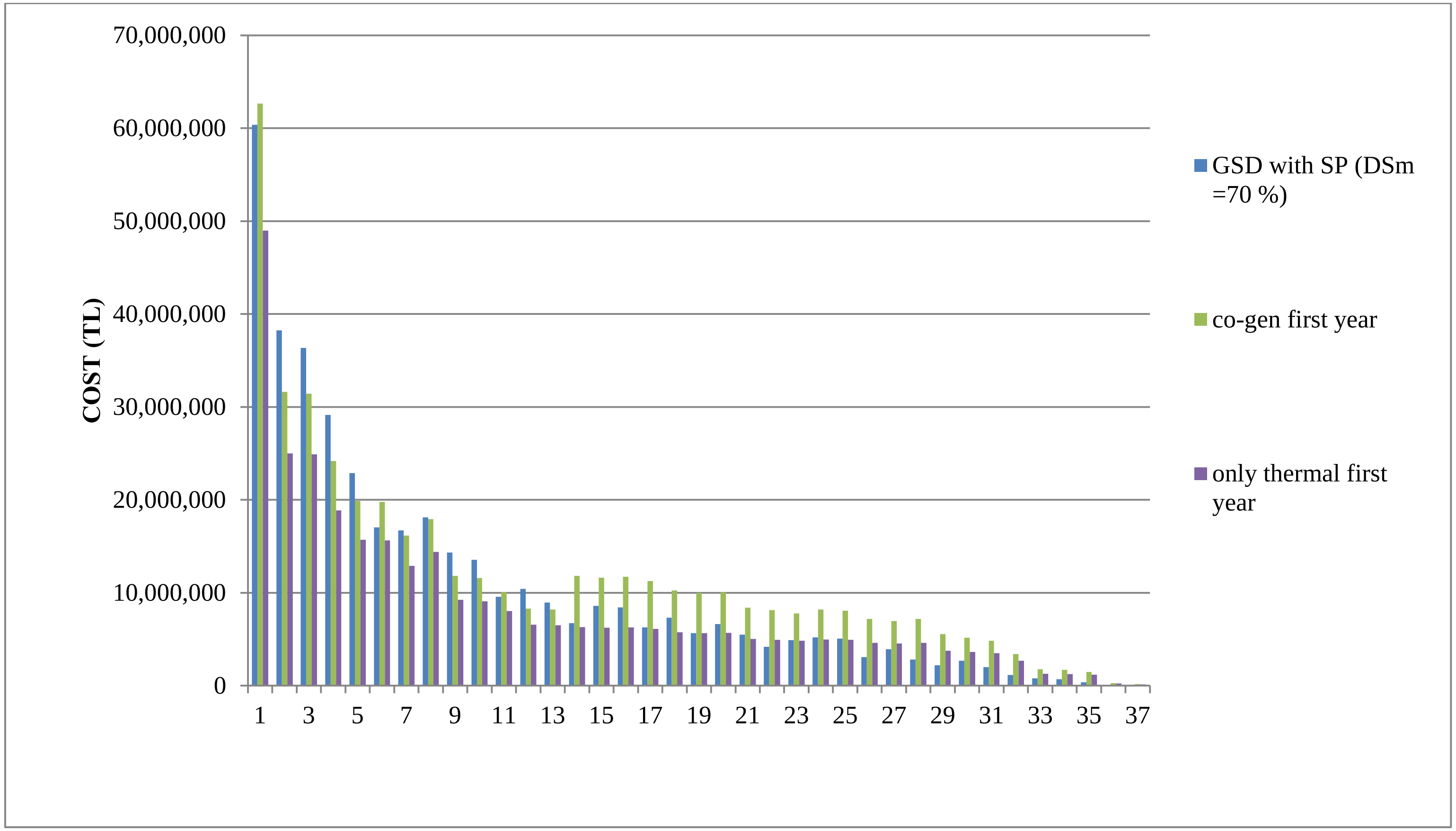


Figure 4.18 Comparison of the costs for differerent sludge drying approches

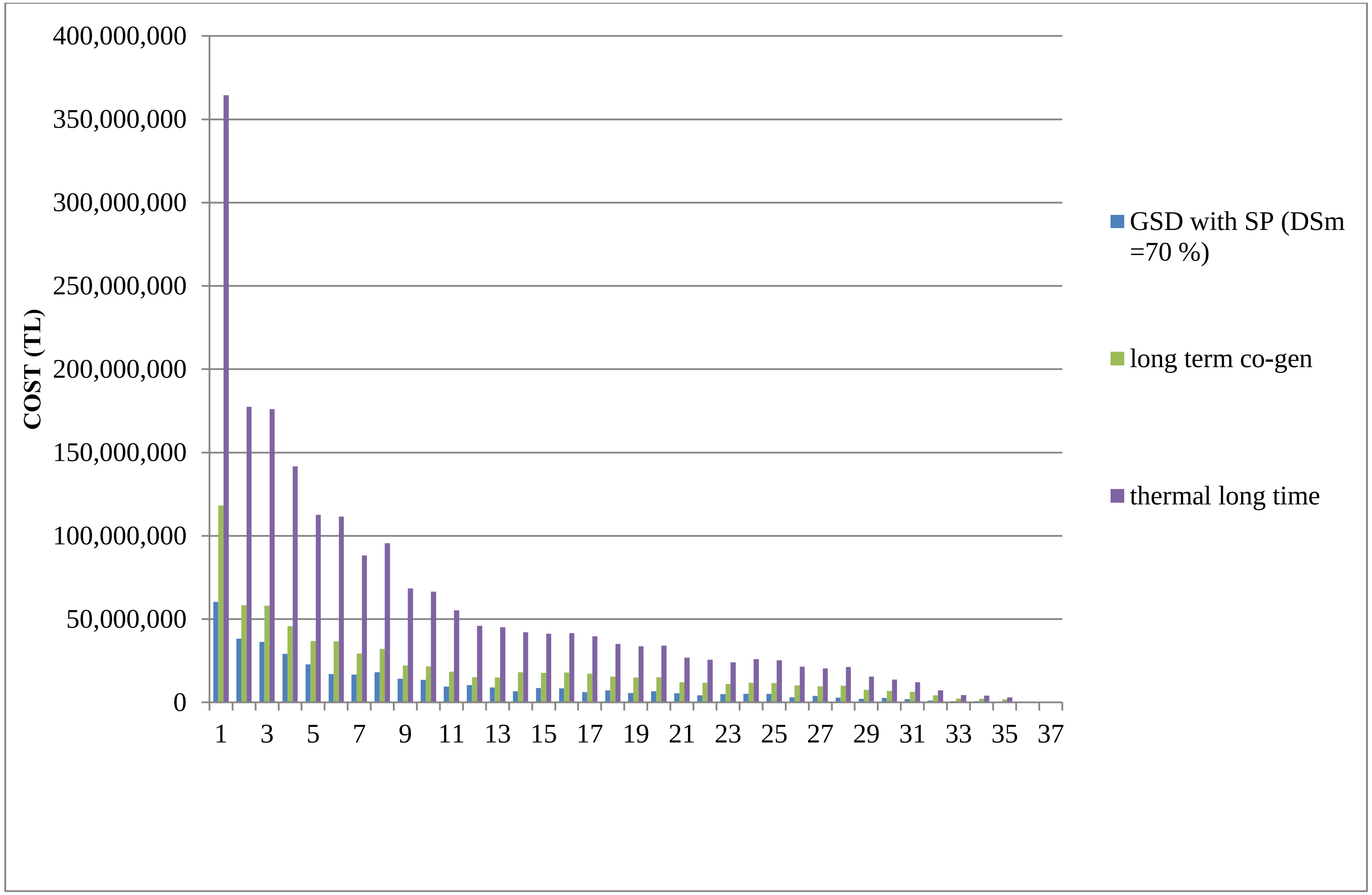


Figure 4.19 Comparison of differerent sludge drying approch cost in terms of long time

The cost of investment including one year operation is cheaper for thermal drying is than other sludge drying options (Figure 4.18). However, when the comparisons were made just for the energy requirement of the systems in long term (28 years), required energy cost of thermal dryer is the most expensive that also requires high amounts of fossil fuel. Therefore, co-generation thermal dryers would be more feasible for a long term use. While thermal dryer was compared with GSD supported with solar panel systems, investment cost including first year energy costs are close each other. However, when they are compared with long-term operation costs, GSD supported with solar panel system would be cheaper than co-generation system, because it would not require natural gas. As a result, if sufficient area is present for sludge drying GSD supported with solar panel system is the best application for sludge drying for all the WWTPs in this study.

In this study, temporal changes in regional climate were not considered for the WWTPs. Although solar radiation, solar duration and outdoor temperature were obtained from General Directorate of Turkish State Meteorology Service in order to calculate evaporation rate, constraints are not specified as in spatial and temporal distributions. For example, Mediterranean region, Aegean region and southeast Anatolian region have longer solar duration time and high solar radiation (Figure 4.20). Additionally Southeast Anatolian region has very low moisture content than other regions (Figure 4.21) therefore no auxiliary energy may be required to dry sludge until 90 %DS during summer time. For example, Fethiye WWTP can reach up to 85% DS during summer time without using auxiliary heat (Personal Communication with operation engineer). On the other hand, Black Sea region, Marmara region and Center Anatolian region are at north of Turkey; therefore, solar duration and solar radiation are less than for other regions. Hence, some regions, especially Black Sea region, may not reach 70% DS without auxiliary heat even at summer time. These may be important and spatial and temporal variations should also be considered for feasibility. These can be studied in future studies.

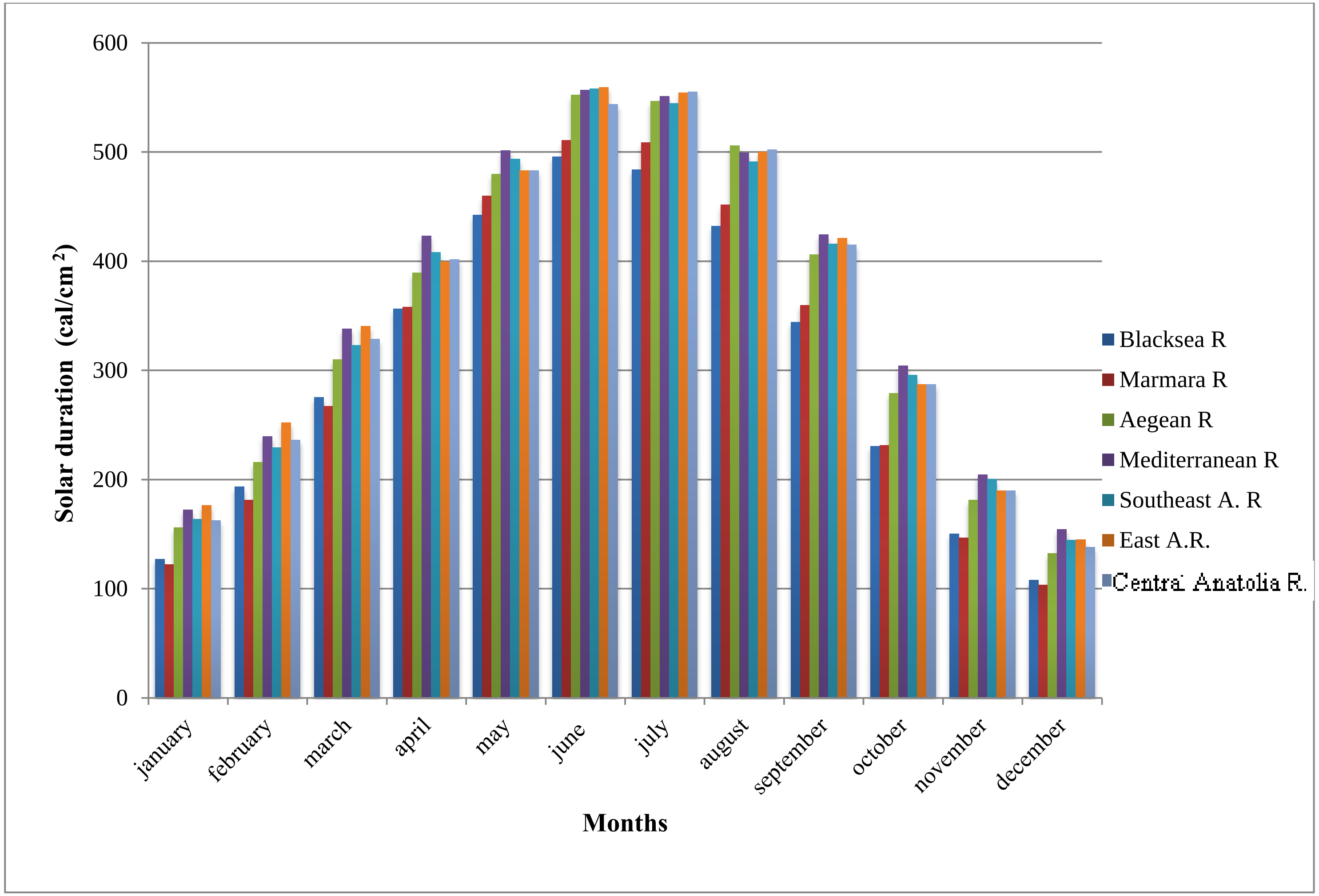


Figure 4.20 Long term monthly mean solar radiation for seven regions

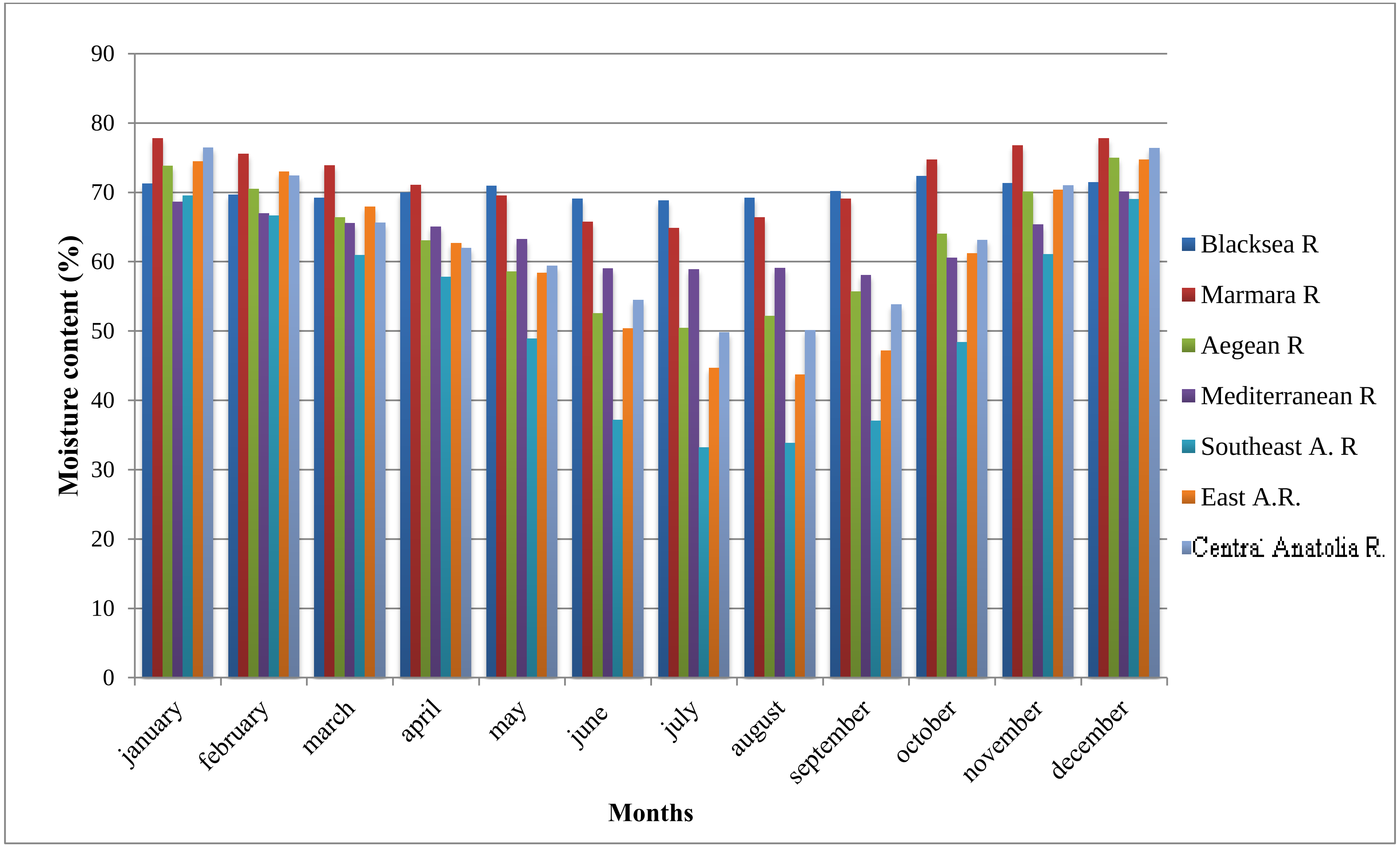


Figure 4.21 Long term monthly mean moisture content for seven regions

Figure 4.22 shows world solar radiation potential. The figure illustrates that solar radiation duration in Black Sea region is similar to the solar radiation duration in south Germany. The solar radiation duration in the Mediterranean region is similar to that for Spain. Therefore, the results obtained in this study for the given regions are compared to the existing facilities in Germany and Spain.

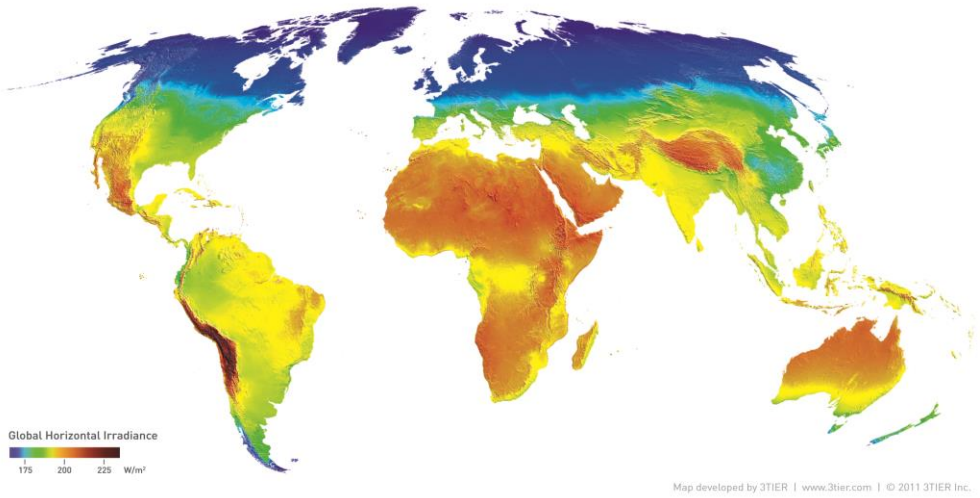


Figure 4.22 Solar radiation map of world (URL5)

Palma de Mallorca in Spain is the largest GSD unit in the world. Its design capacity is 600,000PE and covers 20,000m^2. This GSD is designed to dry 33,000 ton/ year of sludge with the initial DS of 20 %-30 % to up to 60-80%DS. Waste heat input of the plant is provided for 0 to 500kW (Ritterbusch et al., 2012; URL 13). In this GSD, a total of about 27,000 tons of sludge was dried from 19% to 72% DS in 2009. The most similar location and WWTP compared to this one is AK-1. This WWTP produces 36,626 ton/year of sludge with 27%DS. Table 4.11 shows result of optimization scenarioD90C1 for AK-1 WWTP.

Table 4.11 The results for AK-1 WWTP

Scenario	Final dryness	Required sludge area (m^2)	Required auxiliary heat kw	Total Cost
Scenario-D90C1	70%DS$_m$&90%DS	7,338	2,392	9,560,219

Palme de Mallorca example can be extended to the WWTPs in the Mediterranean region such that sludge can be dried up to 70%DS with GSD. In this region using auxiliary heat from the solar panels strictly depends on sunshine duration. Also, required sludge area can be determined using different assumptions. Designed sludge area depends on evaporation rate. Evaporation rate of AK-1 WWTP is 0.35 kg/m^{2}hr, which can be changed by ventilation and mixing ratio. When ventilation and mixing ratio are lower, evaporation rate reduces, hence, required area increases. Ventilation and mixing ratio of Palme de Mallorca is not known therefore, it is hard to compare evaporation rates of two WWTPs. So, comparison was made with area data. Figure 4.23 shows an example (AK-1WWTPS) of the relationship between ventilation, evaporation rate and area.

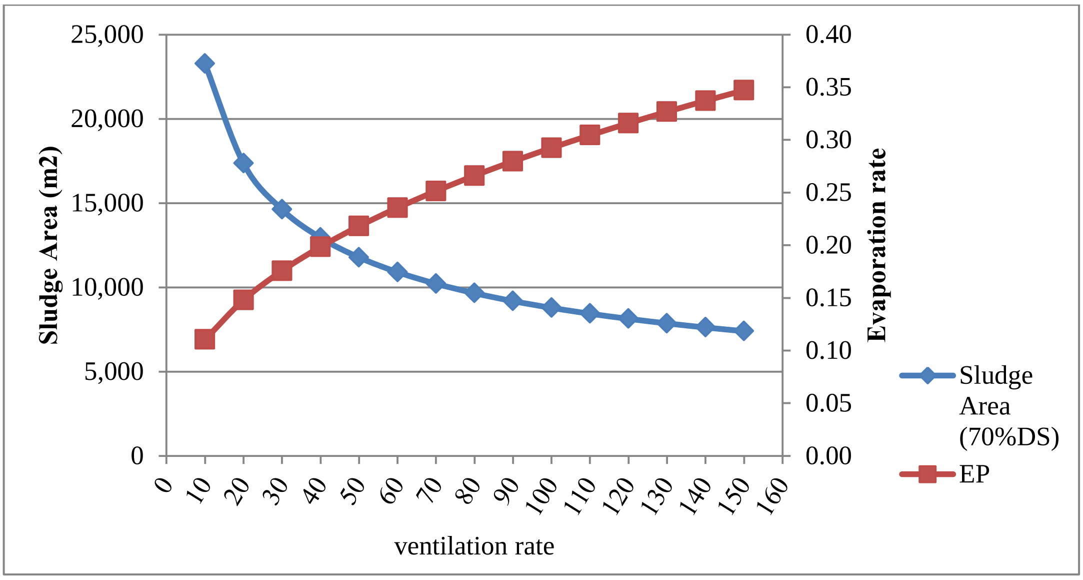


Figure 4.23 Relationship between ventilation rate and sludge area and evaporation rate (AK-1 WWTP)

It is easy to see that while ventilation rate decreases, evaporation rate decreases and sludge area increases past 20,000 m^2(size of Palme de Mallorca GSD). If required area is 20,000m^2, ventilation rate is 20 m/hr (previously, this value was 150 m/hr), then evaporation rate becomes approximately 0.16 kg/m^2.hr.This results shows that evaporation rate can be controlled with ventilation rate. While ventilation rate decreases, evaporation rate and required energy amount decreases therefore GSD area increases.

Oldenburg greenhouse solar dryer in south Germany dries the sludge from 15-30 DS% to 60-70 % DS. This plant can dry 40,000 metric tons of wet sludge per year (44,000 t/yr) on 6,000 m². Also, the plant uses auxiliary energy, which is 7,400 MWh of electricity (Ritterbusch et al., 2012). A similar WWTP exist in Turkey, MAR-10 located in Marmara region where the solar radiation value is closer to the one for Oldenburg, Germany. Sludge production rate of MAR-10 is 24,403 t/yr with 26%DS. Table 4.12 shows a summary of optimization results of D90C1 in MAR-10 WWTP. Based on the optimization MAR-10 required 4 times of the area present in the WWTP located at Oldenburg to dry the sludge up to 90% using 44 MWh auxiliary heats. In the case where MAR-10's area is limited to the area present in Oldenburg WWTP sludge drying unit the DS_f of the sludge could not have exceeded 32% DS without any auxiliary heat but only 104 MWh of auxiliary heat was needed to reach 70% DS or 118 MWh of auxiliary heat was needed to reach 90% DS.

Table 4.12 The results of MAR-10 WWTP

Scenario	Final dryness	Required sludge area (m^2)	Required auxiliary heat MWh	Total Cost
Scenario-D90C1	70%DS_m&90%DS	24,052	44	29,141,172

As a result, the calculated values for the WWTPs in Turkey are comparable with the existing WWTPs in Europe in terms of area and energy requirements. The two examples indicate that while WWTP has large area, required energy cost decreases. AK-1 WWTP has enough area for GSD area; therefore, similar WWTPs can be evaluated by expanding GSD area to reduce energy requirement. On the contrary WWTPs with limited area for GSD area could be modified to use more energy.

CHAPTER 5

CONCLUSION& RECOMMENDATION

Sludge drying process is an essential unit in WWTP that reduces sludge volume and transportation cost but it requires high energy. In order to reduce energy cost and CO_2 emission, GSD is an alternative that needs to be supplemented with an additional system to reach high drying ratios. This study is the first example where GSD supplemented with solar panels as auxiliary heat source was evaluated as an alternative to thermal dryers to dry WWTPs sludge in Turkey. In order to obtain the minimum cost of the unified system (GSD with solar panel); an optimization function was composed in terms of energy requirement. The results indicated that water removal from WWTP sludge with solar panels is less economical compare to water removal with GSD and investment cost of thermal dryer systems. However, it is economical option when comparing it with energy requirement cost.

Sludge drying area is usually limited especially near metropolitan cities. Therefore, while the optimization for GSD was performed different area constrains were taken into account by setting 2 ha (the largest GSD area in the world) as the maximum area available for sludge drying. The results in our study showed that the WWTPs, whose sludge production rate is higher than 5 ton/hr, needed larger than 2 ha area for sludge drying with GSD. Therefore, our study concluded that GSD with solar panels should be preferable at the WWTPs whose sludge production rate is less than 5 ton/hr. This study also indicated that while GSD supported with solar panels are dried sludge nonstop, it required very large solar panel areas. If solar panels are used to get energy only solar duration time, total cost of system and area decrease a large proportion. However, drying process would be take longer time.

Even though our study provided a general understanding where GSD supported with solar panels are economical, several improvements would make the conclusions more solid. In this study, solar duration times, the evaporation rates, temperatures and radiations were assumed either from previous studies or average meteorological measurements however experimental values for every parameter obtained for the regions where WWTP is located would be a more accurate estimation for GSD feasibility and capacity. Additionally, ventilation and mixing ratios affect the evaporation rates and more sophisticated studies should include those parameters. At last, because drying is an intermediary process, DS_f and drying methods depend on the disposal methods. Therefore, before any evolution of suitable drying methods DS_f should be estimated based on disposal method.

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URL 3 Aritma Çamurları Bertaraf Yöntemleri ve İşletme Maliyetleri Remondis Su ve Atık Su Teknolojileri San.ve Tic. A.Ş. from: http://www.csb.gov.tr/dosyalar/images/file/Deniz%20KURT_Aritma%20Camurlari%20Sunum_110117%20(1).pdf (access September 2013)

URL 4 NOAA National Oceanic And Atmospheric Administration – Ocean Explorer http://oceanexplorer.noaa.gov/explorations/deepeast01/background/dumping/dumping.html (access June 2013)

URL 5 Entropy Energy, Solar Potential of Turkey http://www.entropyenergy.net/solar-potential-of-turkey.html (access July and September, 2013)

URL 6 01.04.2013 Tarihinden İtibaren Uygulanacak Elektrik Tarifeleri, sanayi orta gerilim www.tedaş.gov.tr (Access May 2013)

URL 7 Physical characteristics of water http://www.thermexcel.com/english/tables/eau_atm.htm (access April, 2012)

URL 8 Fotovoltaik (Solar) Panel Fiyatlarıhttp://www.limitsizenerji.com/haberler/makaleler/141-fotovoltaik-panel-fiyatlari, (access June 2013)

URL 9 Wholescale Solar http://www.wholesalesolar.com/solar-panels.html (access June 2013)

URL 10 Turkwatt OFFGRID ve ONGRID sistemler http://www.turkwatt.com.tr/ (access June 2013)

URL 11 3TIER Resource Maps http://www.3tier.com/en/support/resource-maps/ (access October, 2013)

URL 12 GüneşPaneliSeçimi http://www.limitsizenerji.com/haberler/makaleler/65-gunes-paneli-secimi

URL 13 Energy efficient, solar sludge drying for large treatment facilities http://www.parkson.com/sites/default/files/documents/document-case-study-palma-de-mallorca-317.pdf(access September 2013)

URL 14 Investigation of Solar Flux Distributions on a Central Tower Receiver http://www.vislab.uq.edu.au/education/sv3/2001/anne/ (access July 2014)

URL 15 Oklahoma to Charge Homeowners Who Install Solar Panels http://www.outsidethebeltway.com/oklahoma-to-charge-homeowners-who-install-solar-panels/ (access July 2014)

URL 16 Aerial Archives | San Francisco http://aerialarchives.photoshelter.com/image/I0000IYSefFMffLo) (access July 2014)

URL 17 Zokazola architecture solar panel tower http://www.zokazola.com/solar_tower.html (access July 2014)

URL 18 MIT's solar cell towers double power output of flat panels http://www.wired.co.uk/news/archive/2012-03/27/solar-cell-towers/viewgallery/275168 (access July 2014)

APPENDIX –A

WWTPs GOOGLE-EARTH VIEW AND THEIR COORDINATES

Table A. 1 WWTPs google-earth view and their coordinates

WWTP	sludge rate (kg/hr)	DS_i	AREA (M^2)	VIEW
EGE-1	25,901	22	232,314	
İÇ-1	13,223	26	454,834	
İÇ-2	11,930	19	135,556	

Table A.1 WWTPs google-earth view and their coordinates (cont'd)

WWTP	sludge rate (kg/hr)	DS_i	AREA (M^2)	VIEW
MAR-10	10,714	26	185,574	
MAR-9	8,321	25	172,339	
AK-4	7,476	18	179,134	
GÜN-1	6,668	27	63,580	

Table A. 1 WWTPs google-earth view and their coordinates (cont'd)

WWTP	sludge rate (kg/hr)	DS_i	AREA (M^2)	VIEW
MAR-3	6,493	20	276,000	
İÇ-3	5,239	27	139,588	
MAR-11	4,927	25	125,751	
AK-1	4,181	27	151,178	

Table A.1 WWTPs google-earth view and their coordinates (cont'd)

WWTP	sludge rate (kg/hr)	DS_i	AREA (M^2)	VIEW
İÇ-4	3,382	25	41,123	
MAR-5	3,170	22	44,715	
AK-3	3,035	24	20,527	
MAR-21	3,016	25	34,846	

Table A.1 WWTPs google-earth view and their coordinates (cont'd)

WWTP	sludge rate (kg/hr)	DS_i	AREA (M^2)	VIEW
MAR-16	2,874	21	90,139	
AK-9	2,757	22	20,570	
MAR-2	2,717	30	140,910	
AK-8	2,606	30	116,470	

Table A.1 WWTPs google-earth view and their coordinates (cont'd)

WWTP	sludge rate (kg/hr)	DS_i	AREA (M^2)	VIEW
MAR-4	2,374	23	63,543	
MAR-14	1,875	25	24,172	
AK-2	1,829	27	91,200	
MAR-20	1,730	28	35,081	

Table A.1 WWTPs google-earth view and their coordinates (cont'd)

WWTP	sludge rate (kg/hr)	DS_i	AREA (M^2)	VIEW
MAR-19	1,726	22	17,748	
MAR-12	1,702	23	37,050	
AK-7	1,339	20	30,096	
MAR-17	1,318	23	43,771	

Table A.1 WWTPs google-earth view and their coordinates (cont'd)

WWTP	sludge rate (kg/hr)	DS_i	AREA (M^2)	VIEW
AK-5	1,217	13	20,100	
AK-6	994	24	52,736	
MAR-7	868	25	26,866	
MAR-1	750	25	77,250	

Table A.1 WWTPs google-earth view and their coordinates (cont'd)

WWTP	sludge rate (kg/hr)	DS_i	AREA (M^2)	VIEW
MAR-13	393	25	16,575	
MAR-18	263	23	19,116	
MAR-6	235	22	14,185	
MAR-15	123	2	-	

Table A.1 WWTPs google-earth view and their coordinates (cont'd)

WWTP	sludge rate (kg/hr)	DS_i	AREA (M^2)	VIEW
KAR-1	10	15	2,161	
MAR-8	4	40	-	

APPENDIX-B

NUMERATION OF WWTPs

Numeration	WWTPs
1	EGE1
2	İÇ1
3	İÇ2
4	MAR10
5	MAR9
6	AK4
7	GÜN1
8	MAR3
9	İÇ3
10	MAR11
11	AK1
12	İÇ4
13	MAR5
14	AK3
15	MAR21
16	MAR16
17	AK9
18	MAR2
19	AK8
20	MAR4
21	MAR14
22	AK2
23	MAR20
24	MAR19
25	MAR12
26	AK7
27	MAR17
28	AK5
29	AK6
30	MAR7
31	MAR1
32	MAR13
33	MAR18
34	MAR6
35	MAR15
36	KAR1
37	MAR8

APPENDIX-C

THE RESULTS OF SCENARIO D90C1

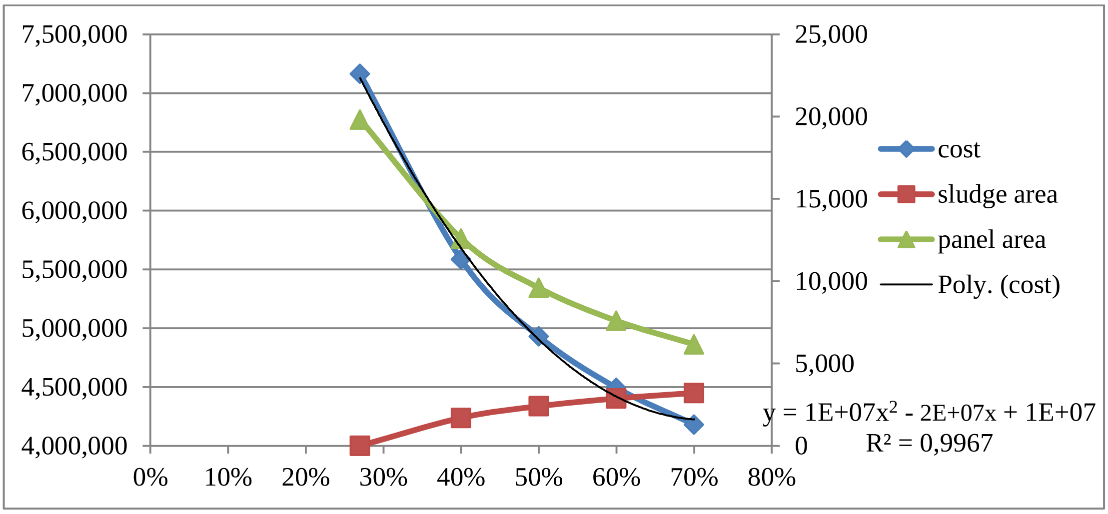

Figure C. 1 AK-2 WWTP

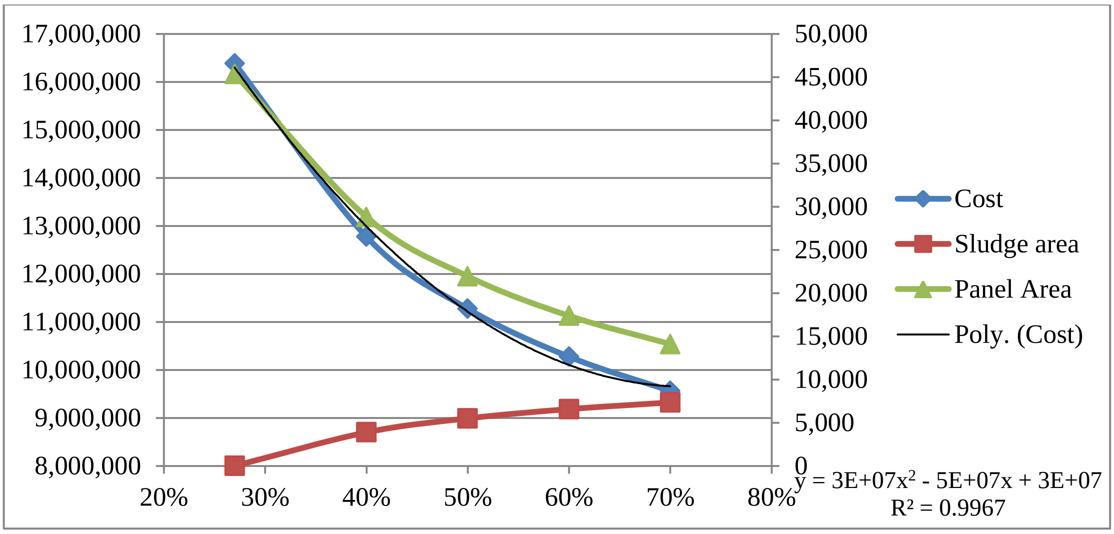

Figure C. 2 AK-1 WWTP

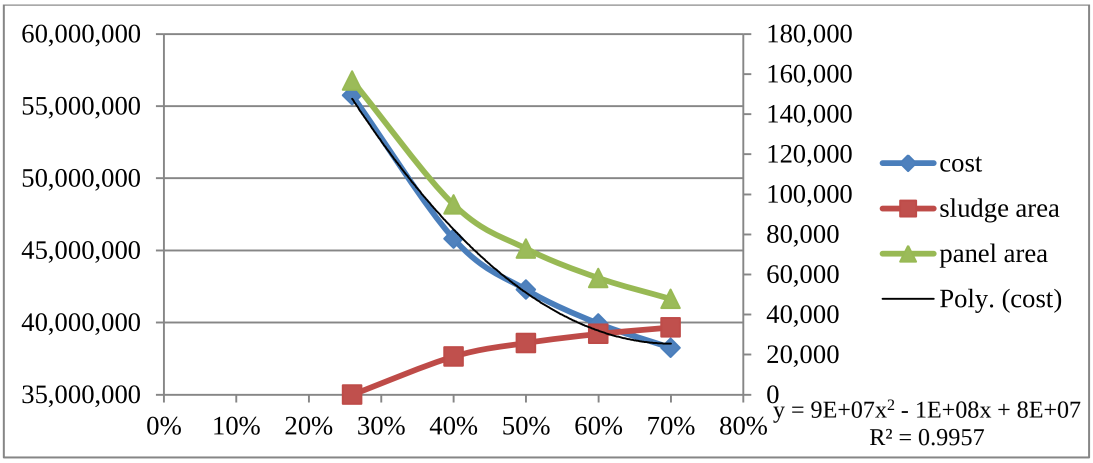

Figure C. 3 İÇ-1 WWTP

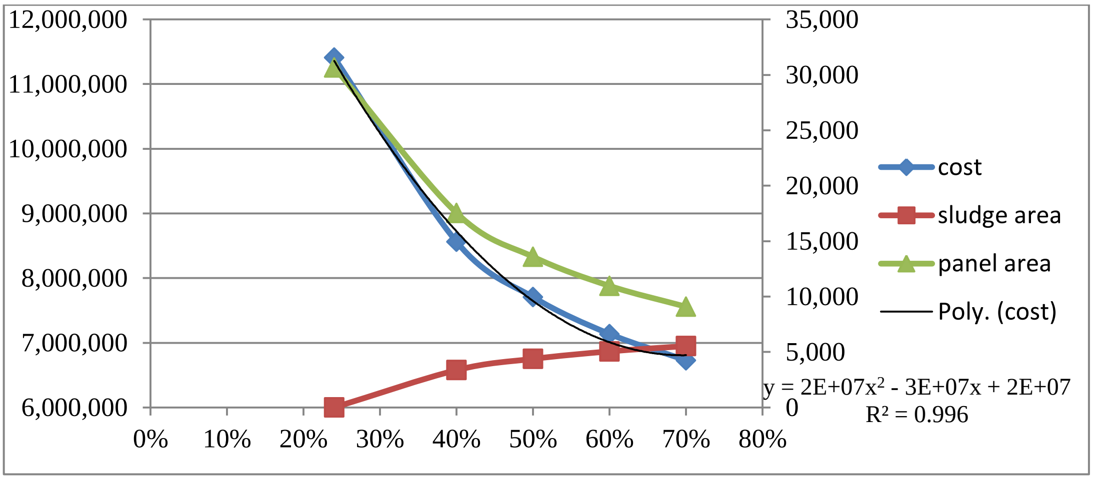

Figure C. 4 AK-3 WWTP

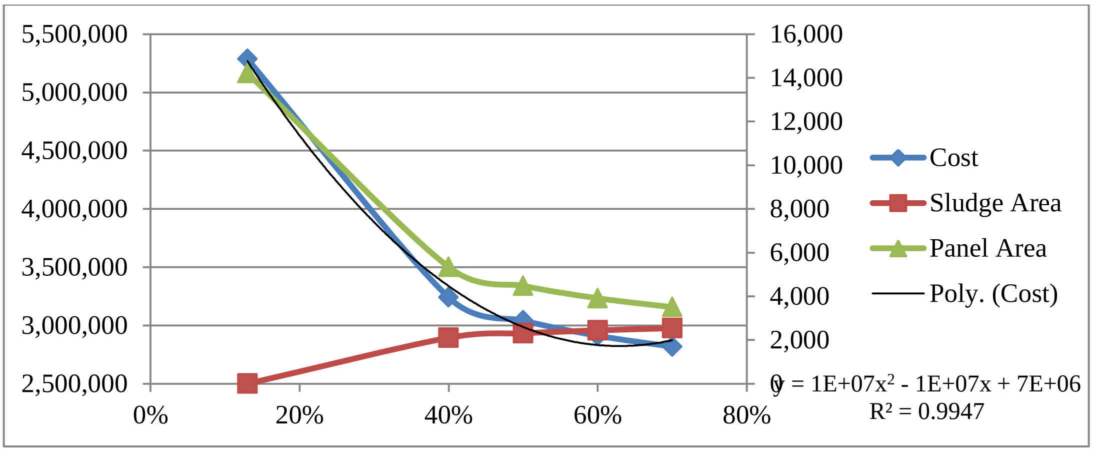

Figure C. 5 AK-5 WWTP

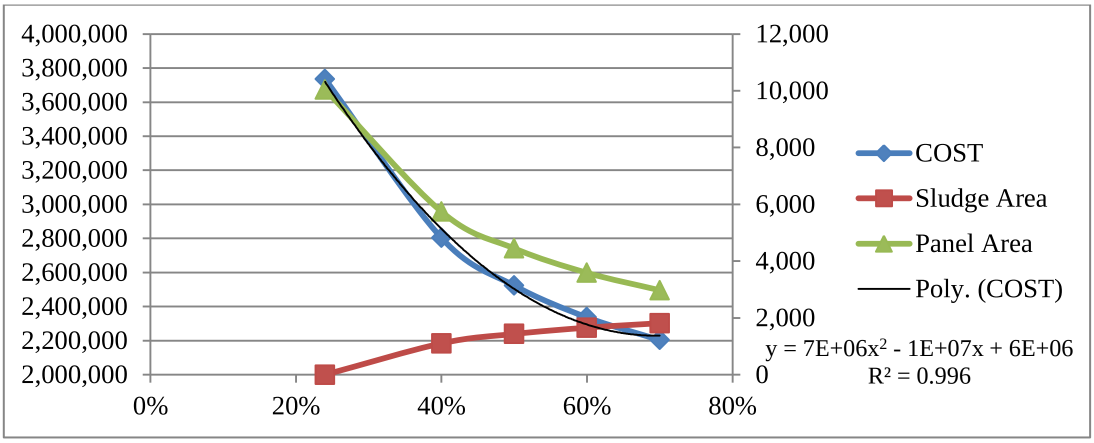

Figure C. 6 AK-6 WWTP

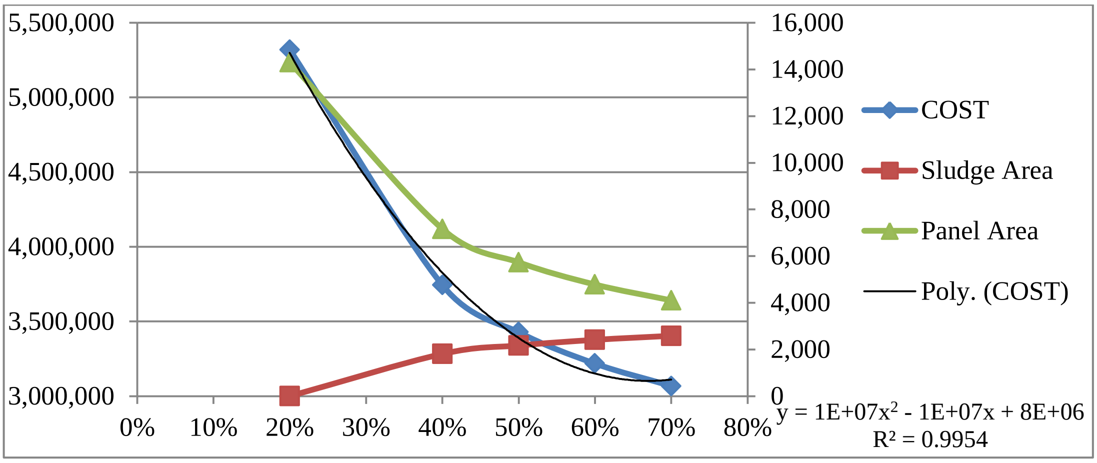

Figure C. 7 AK-7 WWTP

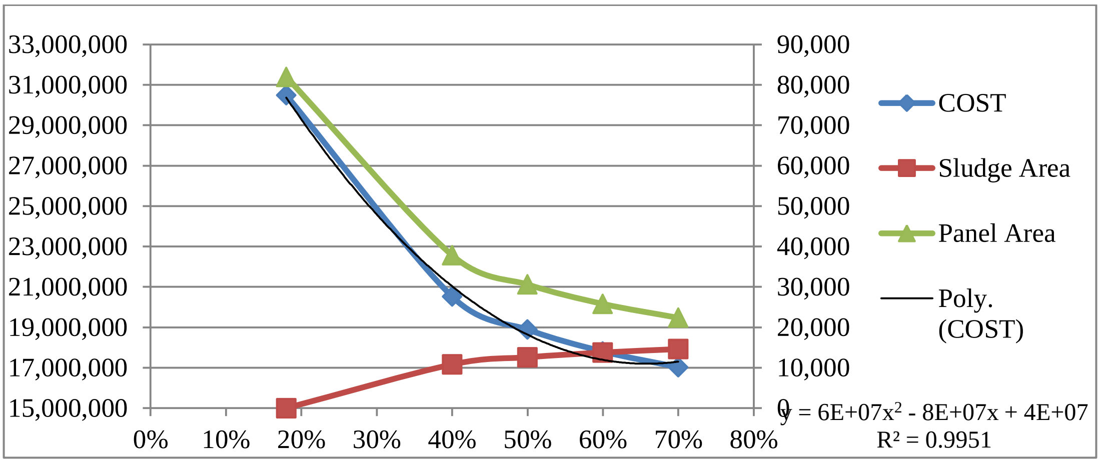

Figure C. 8 AK-4 WWTP

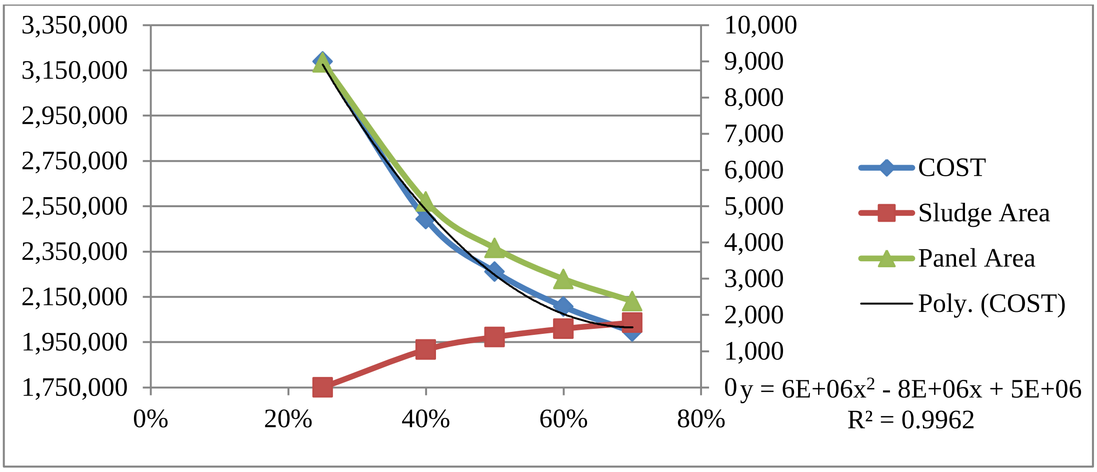

Figure C. 9 MAR-1 WWTP

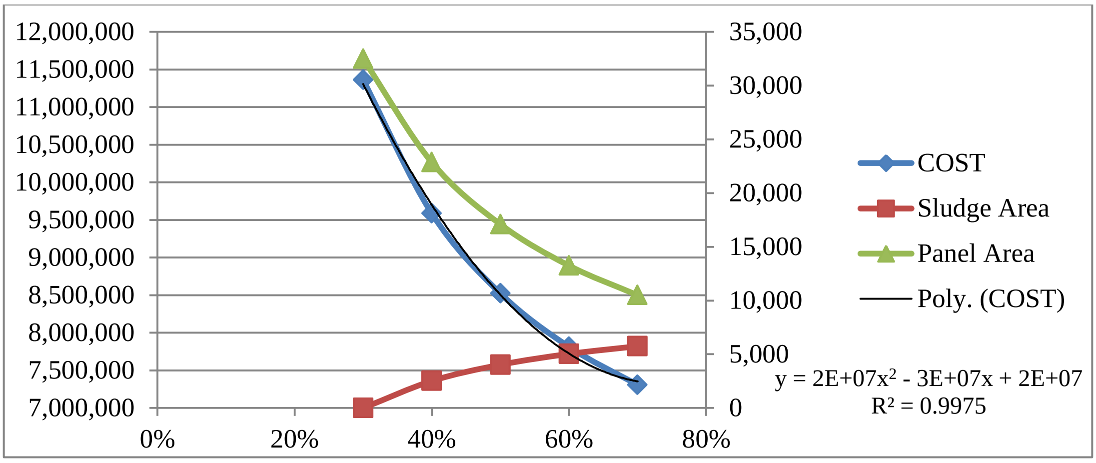

Figure C. 10 MAR-2 WWTP

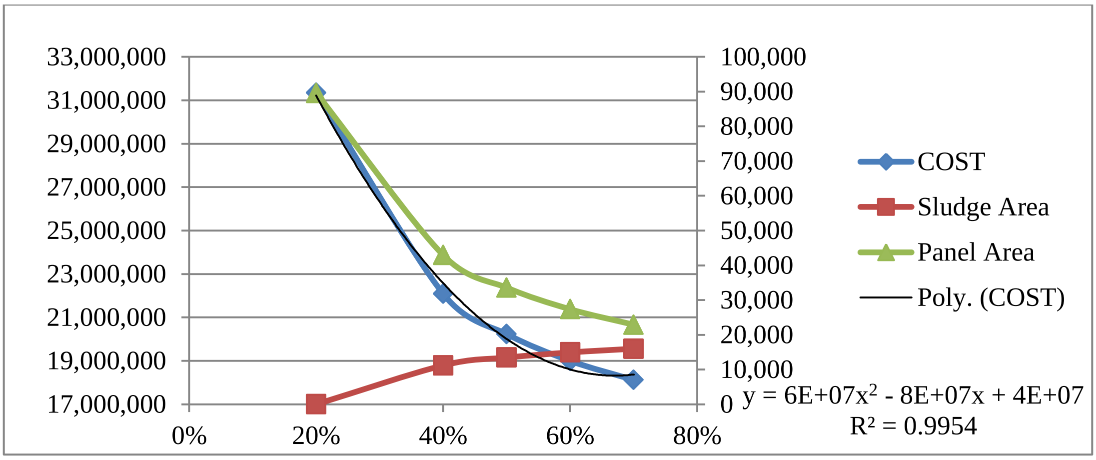

Figure C. 11 MAR-3 WWTP

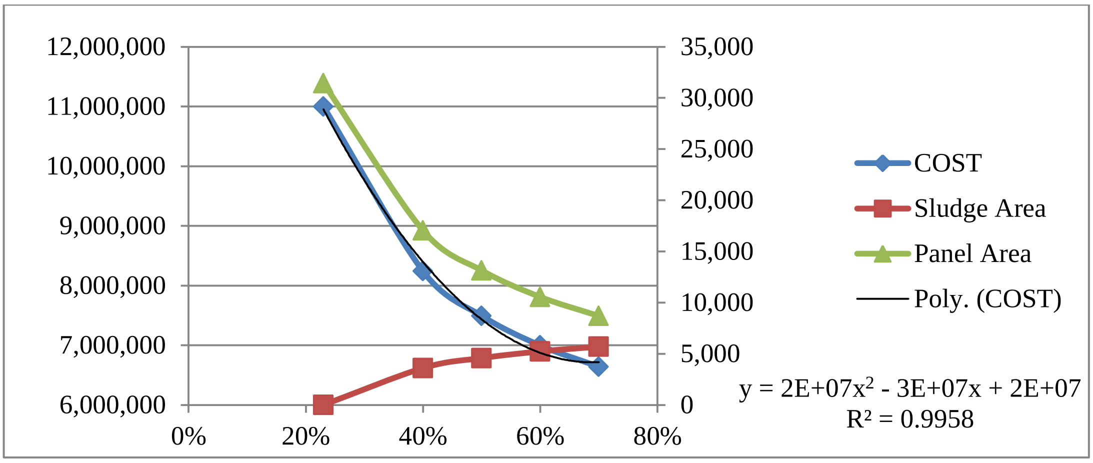

Figure C. 12 MAR-4 WWTP

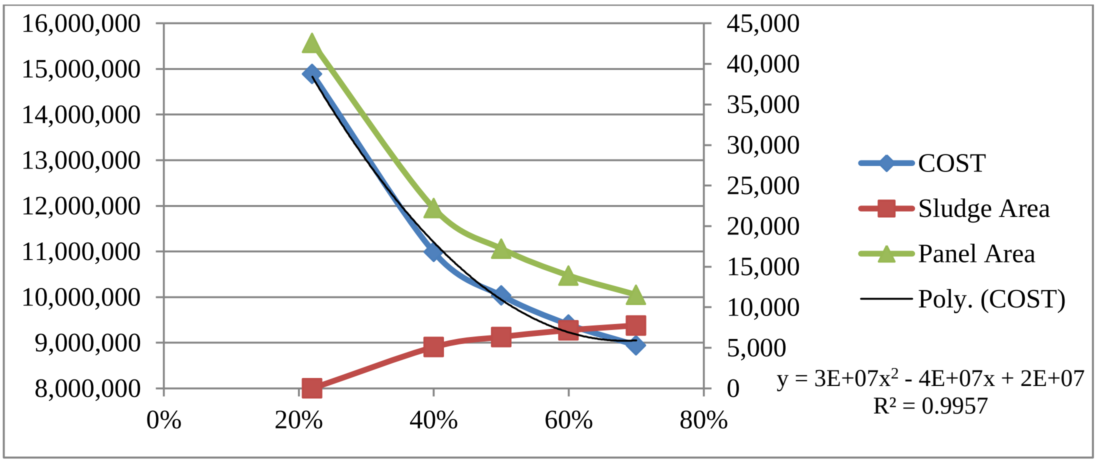

Figure C. 13MAR-5 WWTP

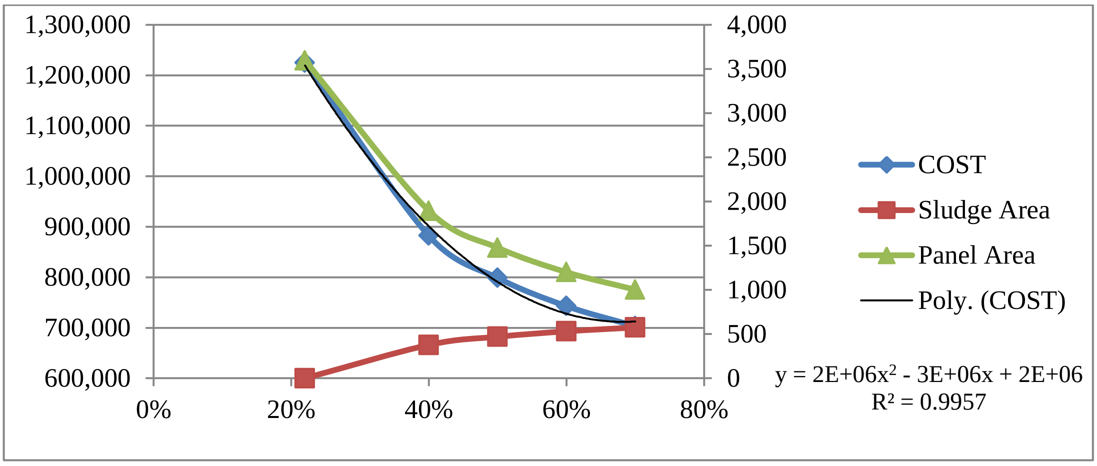

Figure C. 14 MAR-6 WWTP

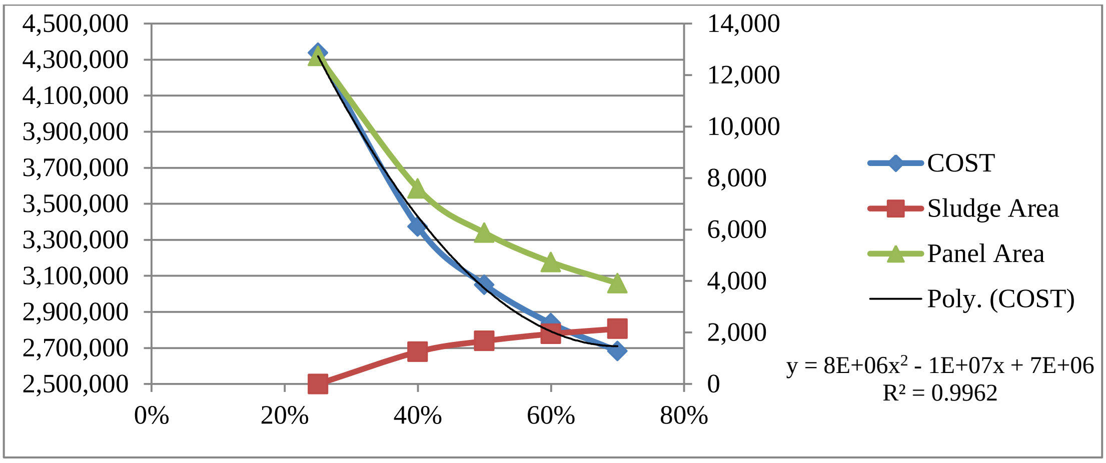

Figure C. 15 MAR-7 WWTP

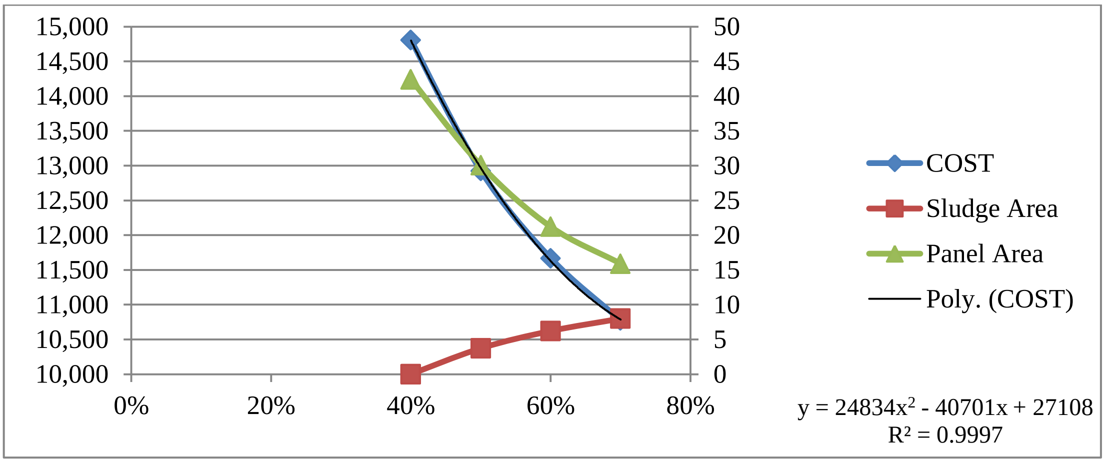

Figure C. 16 MAR-8 WWTP

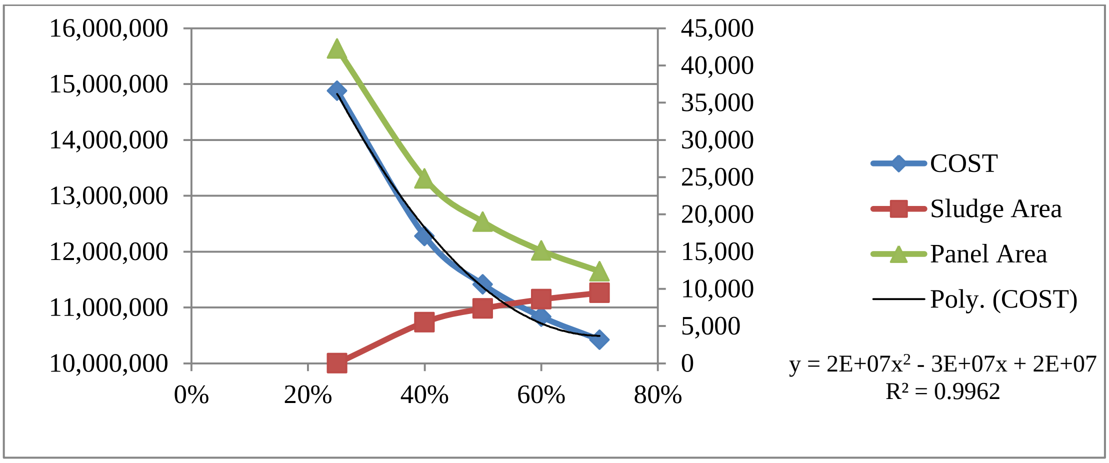

Figure C. 17 İÇ-4 WWTP

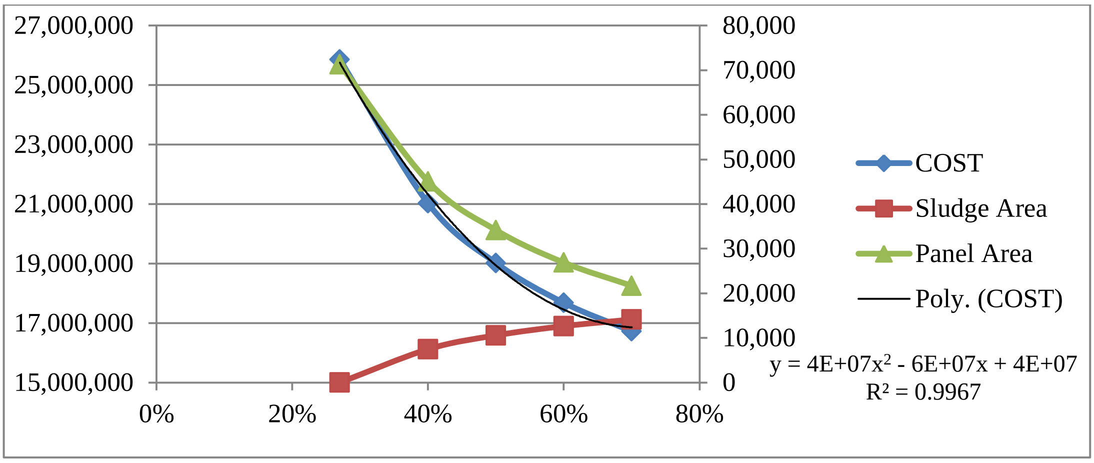

Figure C. 18 GÜN-1 WWTP

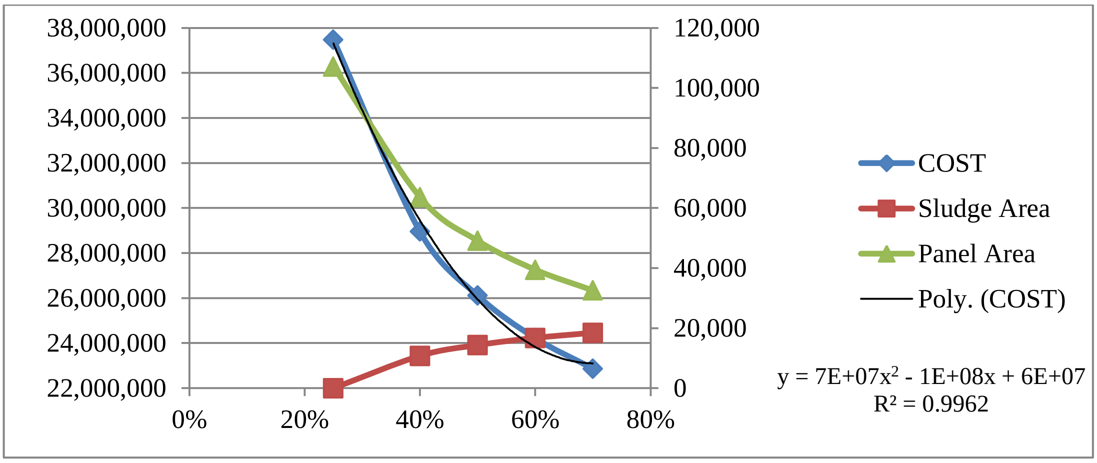

Figure C. 19 MAR-9 WWTP

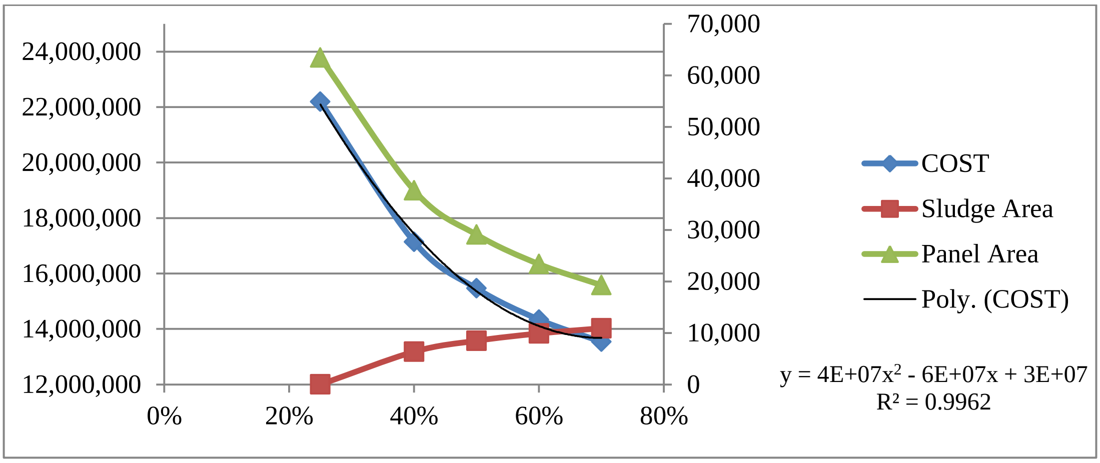

Figure C. 20 MAR-11 WWTP

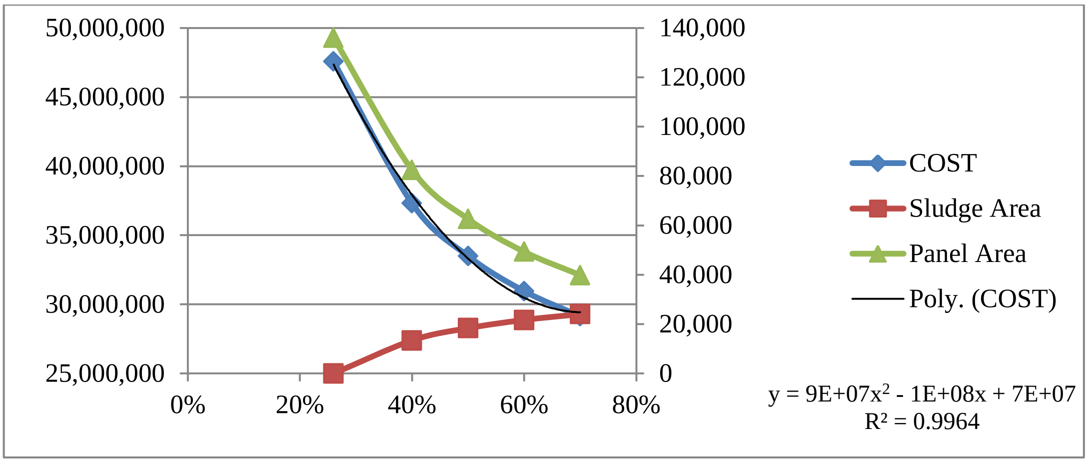

Figure C. 21 MAR-10 WWTP

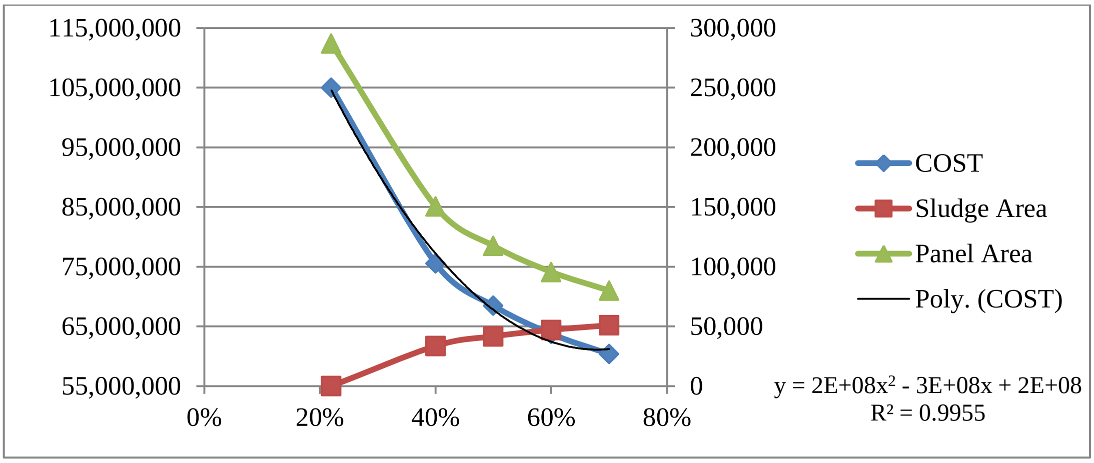

Figure C. 22 EGE-1 WWTP

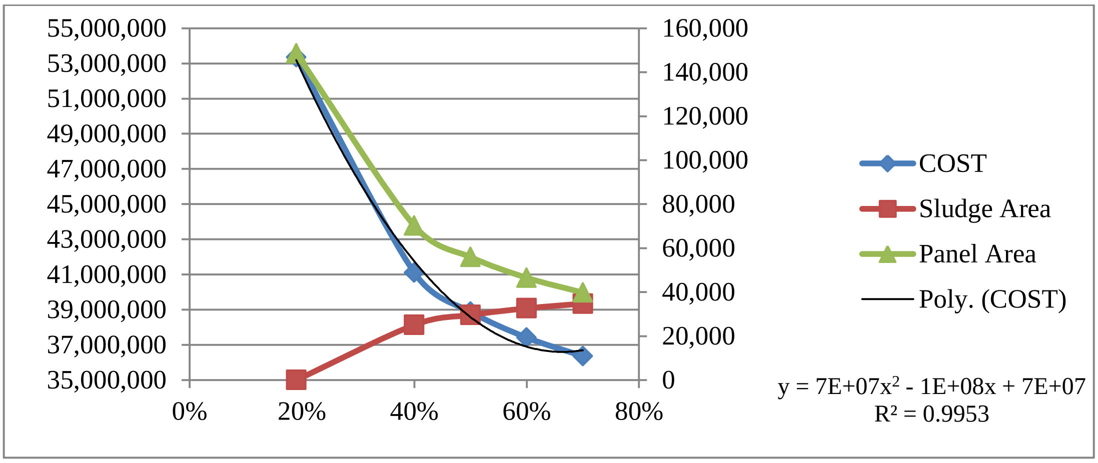

Figure C. 23 İÇ-2 WWTP

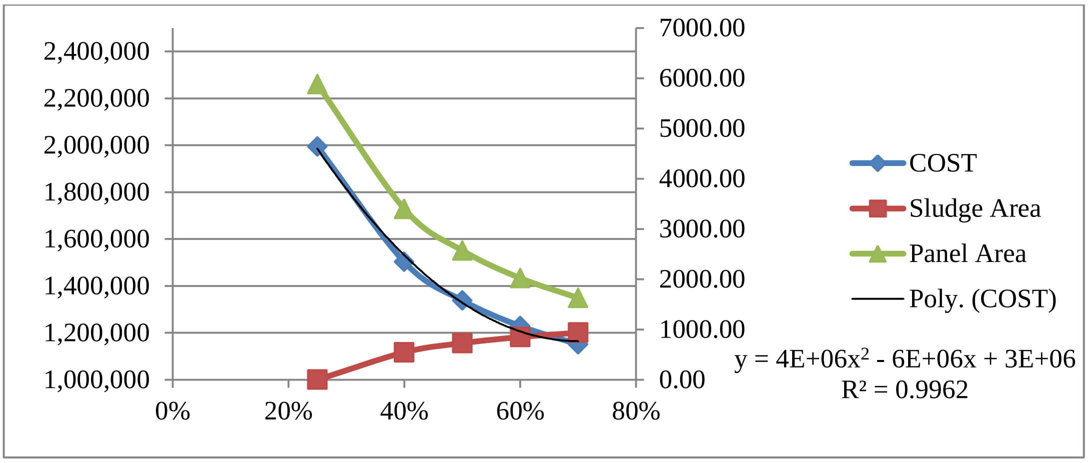

Figure C. 24 MAR-13 WWTP

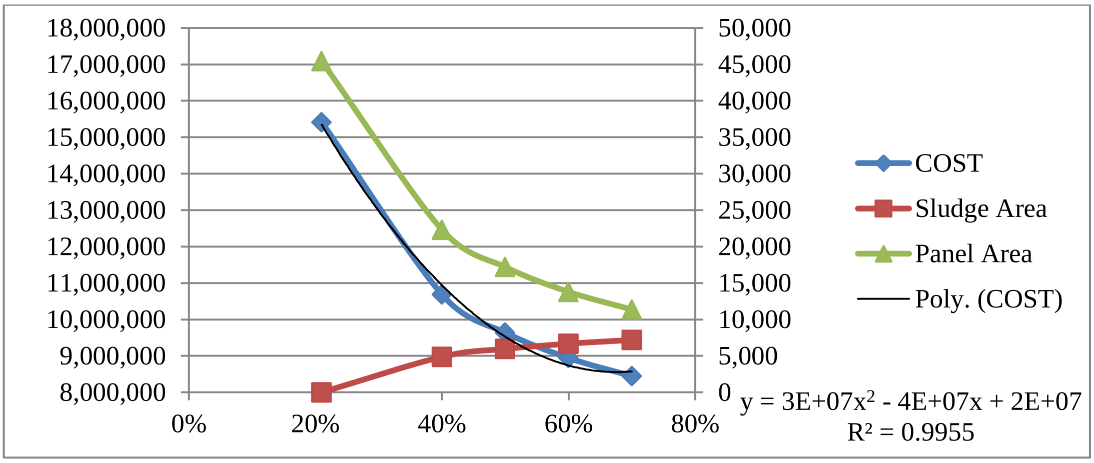

Figure C. 25 MAR-16 WWTP

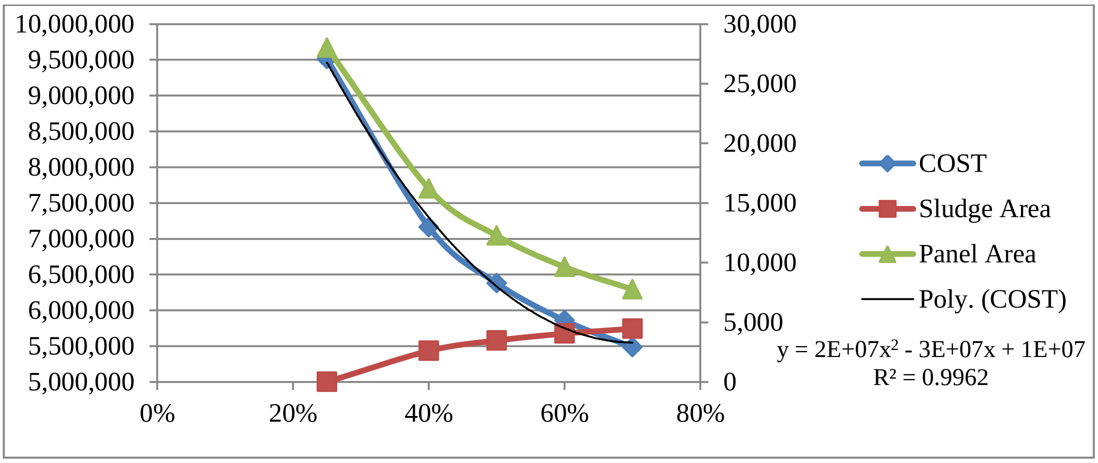

Figure C. 26 MAR-14 WWTP

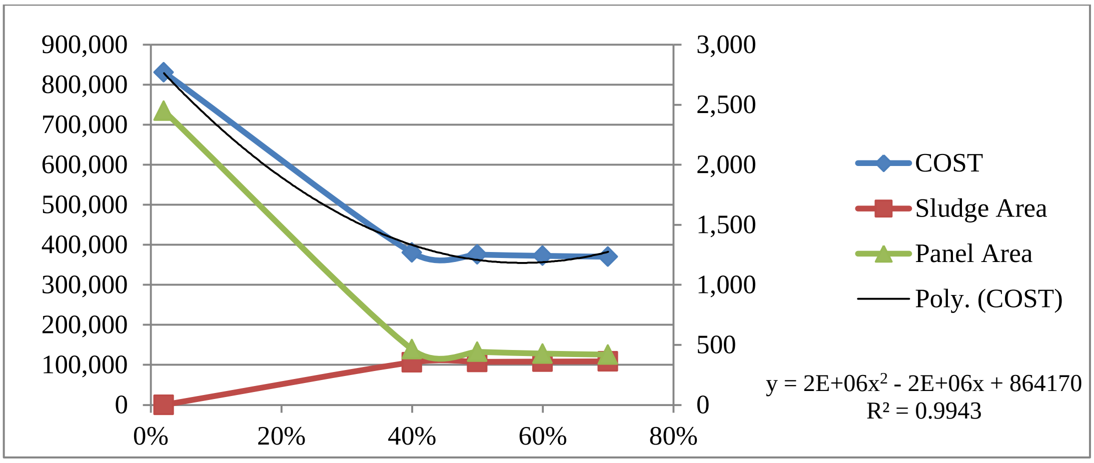

Figure C. 27 MAR-15 WWTP

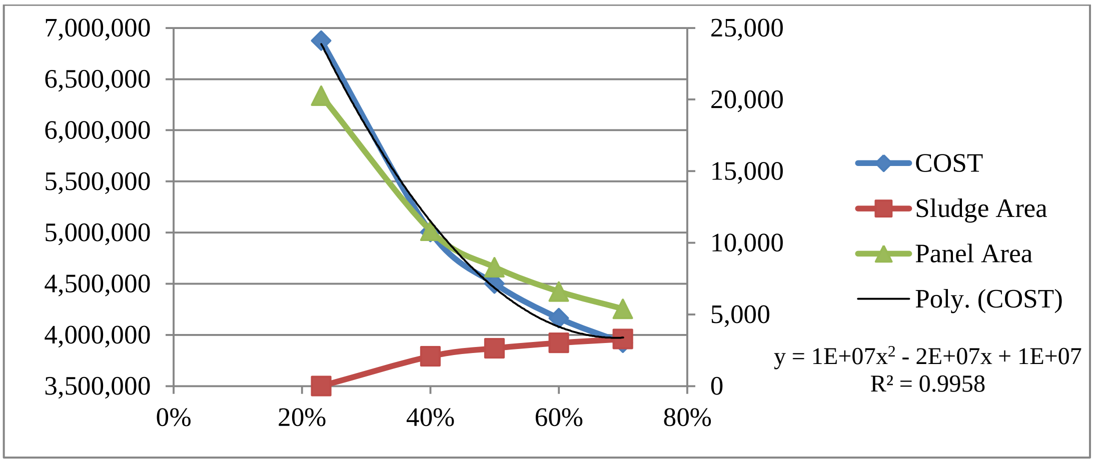

Figure C. 28 MAR-17 WWTP

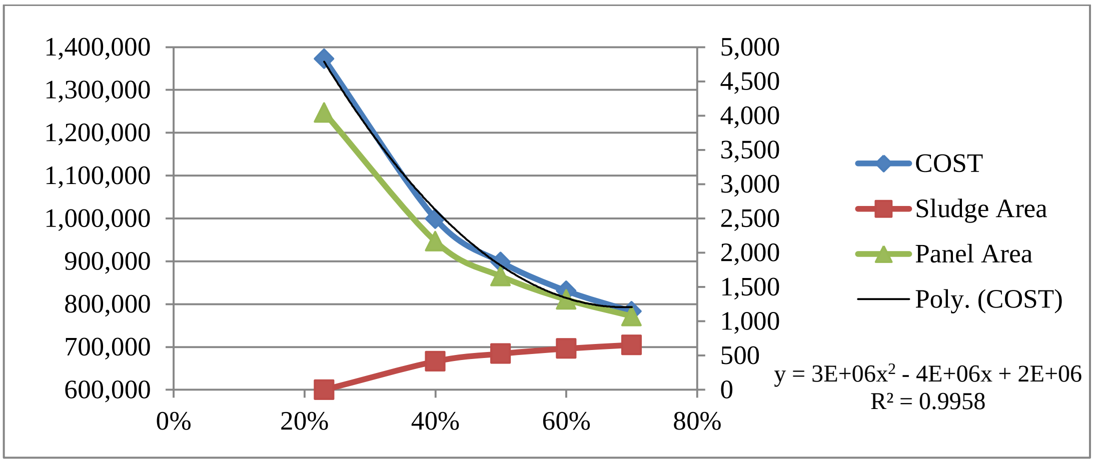

Figure C. 29 MAR-18 WWTP

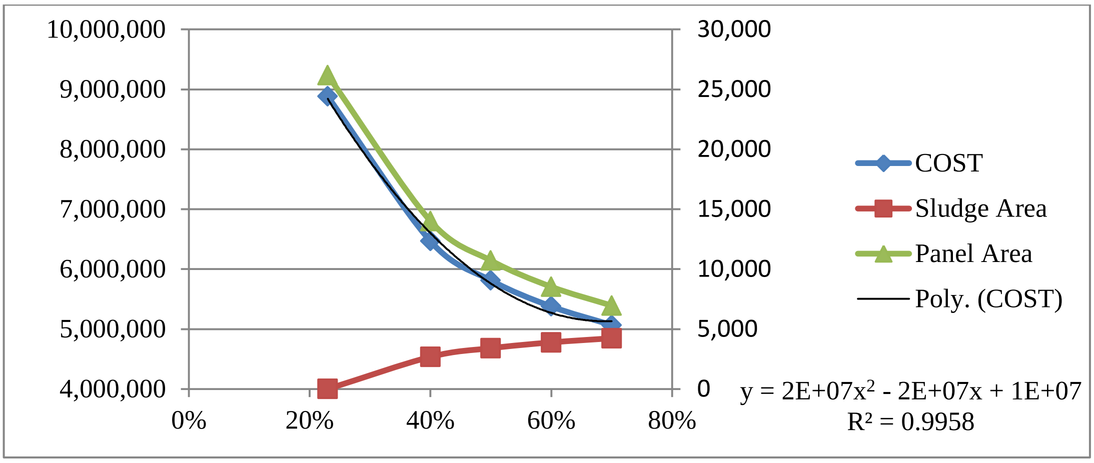

Figure C. 30 MAR-12 WWTP

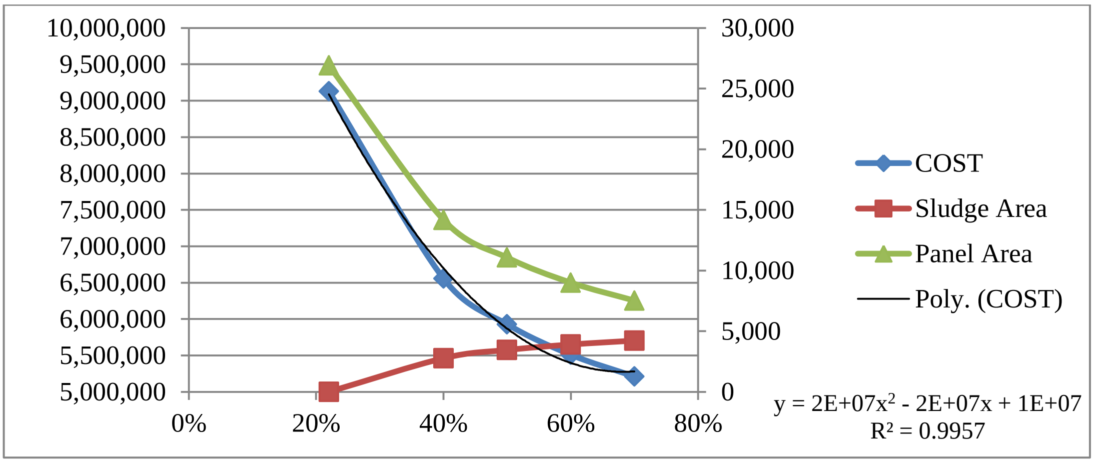

Figure C. 31 MAR-19 WWTP

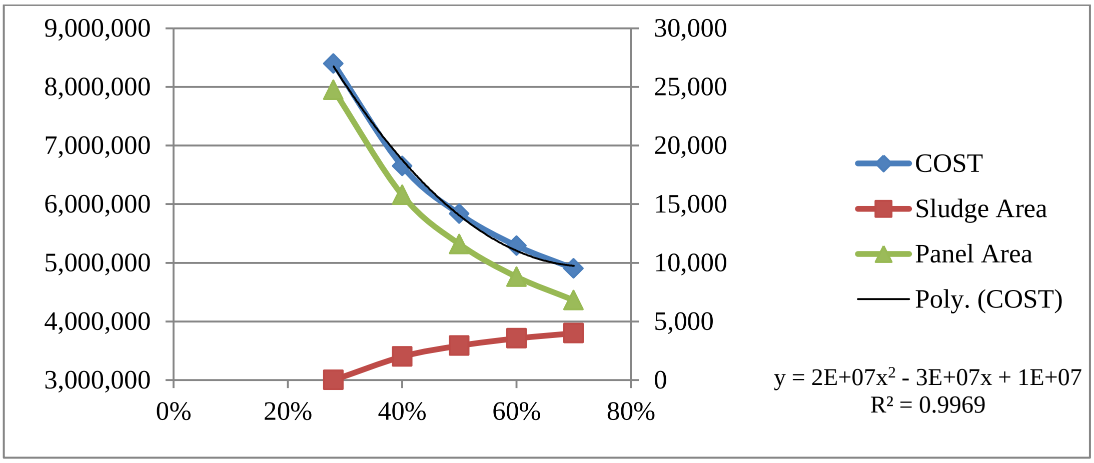

Figure C. 32 MAR-20 WWTP

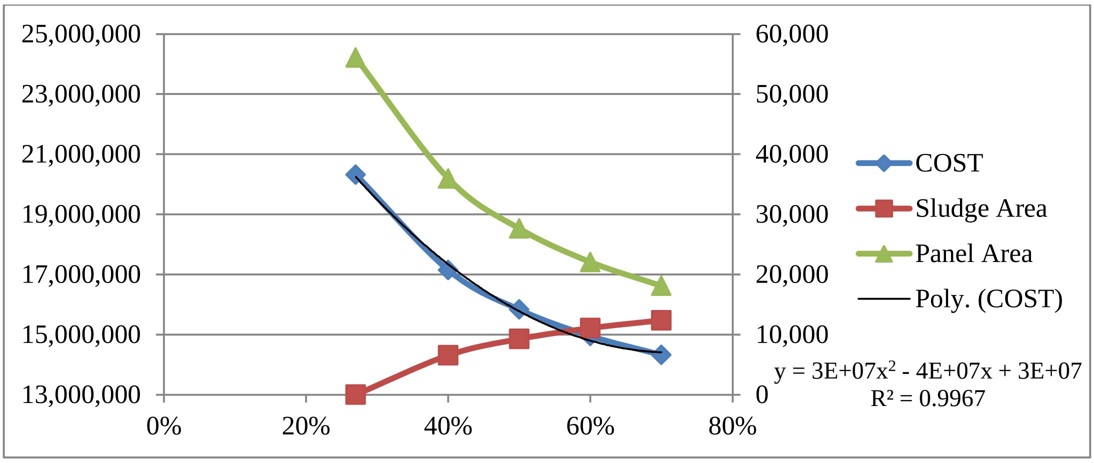

Figure C. 33 İÇ-3 WWTP

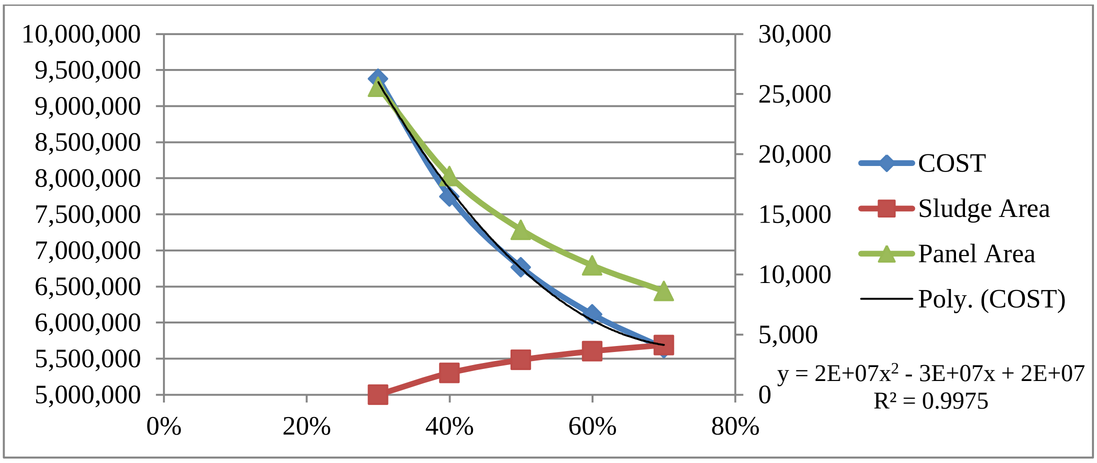

Figure C. 34 AK-8 WWTP

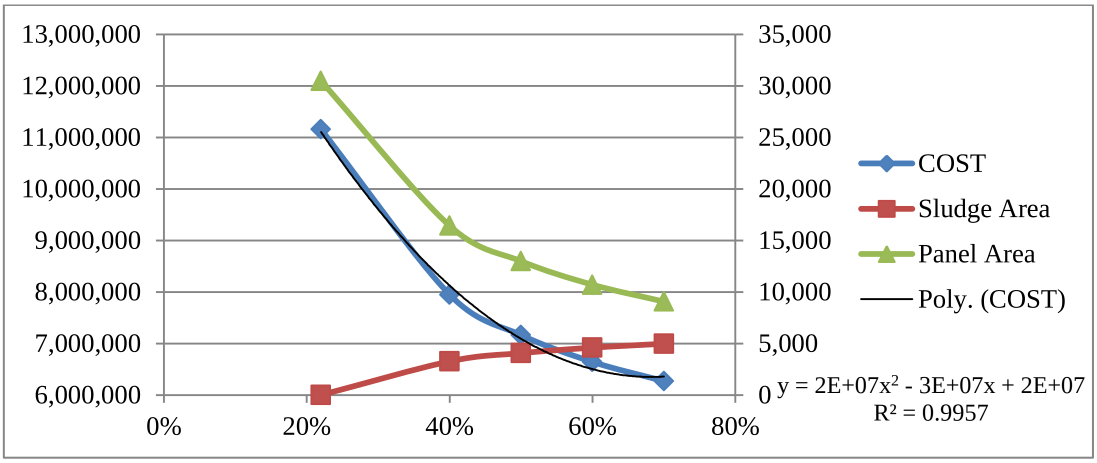

Figure C. 35 AK-9 WWTP

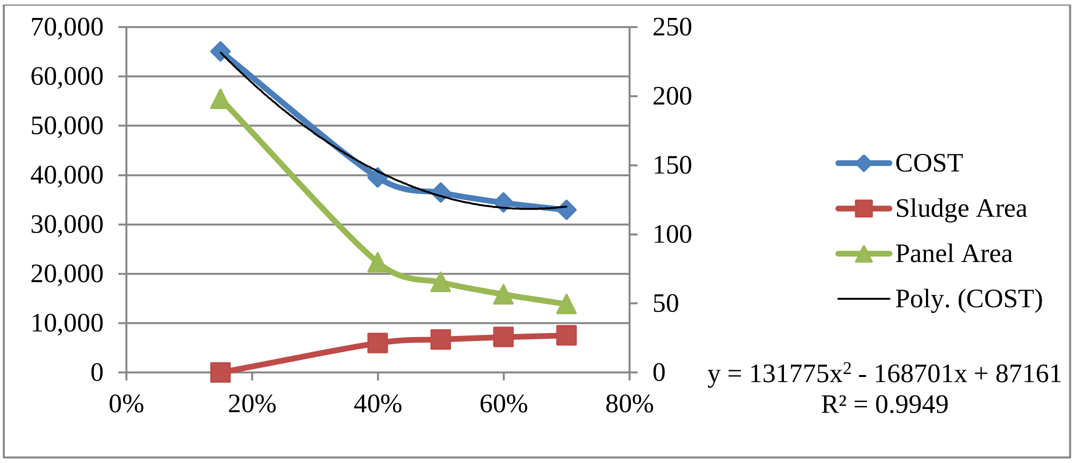

Figure C. 36 KAR-1 WWTP

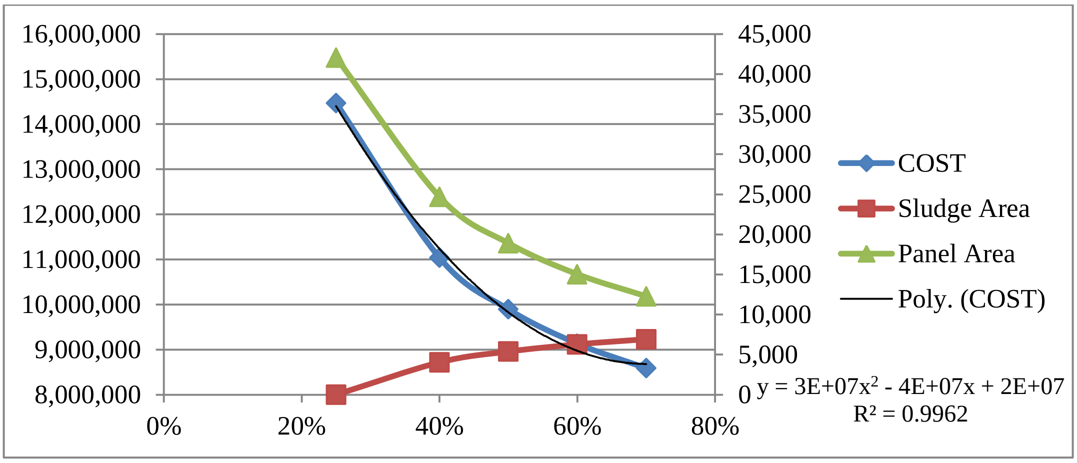

Figure C. 37 MAR-21 WWTP