DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

LINEAR CONTROLLER DESIGN AND IMPLEMENTATION ON A TWO AXIS SUN TRACKER SYSTEM

by
Tuğçe ÜNVER

February, 2020
İZMİR

LINEAR CONTROLLER DESIGN AND IMPLEMENTATION ON A TWO AXIS SUN TRACKER SYSTEM

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"LINEAR CONTROLLLER DESIGN AND IMPLEMENTATION ON A TWO AXIS SUN TRACKER SYSTEM"** completed by **TUĞÇE ÜNVER** under supervision of **ASST. PROF. DR AYTAÇ GÖREN** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

....

Asst. Prof. Dr. Aytaç GÖREN

Supervisor

....

Assoc. Prof. Dr. Mutlu BOZTEPE

(Jury Member)

....

Prof. Dr. Hasan ÖZTÜRK

(Jury Member)

Prof. Dr. Kadriye ERTEKİN

Director

Graduate School of Natural and Applied Sciences

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Tuğçe ÜNVER

LINEAR CONTROLLER DESIGN AND IMPLEMENTATION ON A TWO AXIS SUN TRACKER SYSTEM

ABSTRACT

Producing energy in sustainable and efficient ways is an important issue considering rapidly growing earth population and higher demands. In today's developing technology, solar energy production is a substantial solution. Sun tracker systems following the sun rays from sunrise to sunset and combined with closed-loop control technics and improved storage methods proved to be very efficient compared to stationary solar systems.

In this study, research and development has been done in order to increase the efficiency of solar tracking systems. The optimum angle and orientation to the weather conditions are important to obtain maximum efficiency from the sun rays. In order to be used in control techniques that will provide this orientation, the radiation values have been recorded by taking the prefabricated reference at Izmir Dokuz Eylul University Tinaztepe Campus for one year and new mathematical models have been developed considering these values. In line with the results obtained, at the same time, designs suitable for urban planning were created. System designs have been proposed to solve the problem of energy production in settlements in accordance with the foreseen modular city designs. And the system behavior can be insufficient so monitoring the system response to drive the system through desired response is necessary so controllers were designed to provide better system dynamics.

Keywords: Solar power, sun tracker, solar radiation, modular city

İKİ EKSENLİ GÜNEŞ TAKİP SİSTEMİ İÇİN DOĞRUSAL KONTROLCÜ TASARIMI VE UYGULAMASI

ÖZ

Günümüzde sürdürülebilir enerji üretimi önemli bir mühendislik problemi olarak görülmektedir. Üretim yöntemleri oldukça çeşitlidir. Verim ve sürdürülebilirlik açısından ise güneş enerjisi kullanımı gün geçtikçe daha da yaygınlaşmaktadır. Sistem verimini arttırmaktaki en önemli parametreler güneş ışınlarının sisteme dik gelmesini sağlayarak maksimum yararlanmak, çıkış voltajını en yüksek enerjinin elde edilebileceği nokta sağlamak, depolama yöntemlerini daha etkin hale getirmek olarak sıralanabilir. Bu doğrultuda güneş takip sistemleri devreye girer. Gün doğumundan batımına kadar güneş ışınlarını takip eden sistemlerin pozisyon geri beslemeli kapalı devre kontrolleriyle, iyileştirilmiş depolama yöntemleriyle bir araya geldiğinde, sabit sistemlere göre oldukça verimli olduğu gözlemlenmiştir. Güneş takip sistemleri ve geliştirilmesi akademi ve endüstride ilgi çeken bir çalışma alanı olarak görülmektedir.

Bu çalışmada, belirlenen bölgede kaydedilen ışınım değerleri ve çalışma çerçevesinde geliştirilen güneş ışınım modelinden yola çıkılarak, güneş takip sistemlerinin verimliliğini arttırmak doğrultusunda, araştırma ve geliştirmeler yapılmaya çalışılmıştır. Güneş ışınlarından maksimum verim alabilmek için optimum açı ve hava koşullarına uygun yönelim önemlidir. Bu yönelimi sağlayacak kontrol tekniklerinde kullanılmak üzere bir yıl boyunca İzmir Dokuz Eylül Üniversitesi Tınaztepe Kampüsünde bulunan prefabrik referans alınarak ışınım değerleri kaydedilmiştir ve bu değerler göz önünde bulundurularak yeni matematiksel modeller geliştirilmiştir. Gelecekte öngörülen modüler şehir tasarımlarına uygun yerleşim birimlerinde enerji üretim sorununun çözülmesine yönelik sistem tasarımları önerilmiştir. Sistem davranışı yetersiz olabilir, bu nedenle sistemi istenen tepki ile yönlendirmek için sistemin cevabını izlemek gereklidir, Bu yüzden daha iyi sistem dinamiği sağlamak için kontrolcü tasarımı yapılmıştır.

Anahtar kelimeler: Güneş paneli, solar takipçi, ışınım, modüler şehir

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CHAPTER ONE
INTRODUCTION

Today energy infrastructure causes 2.5 to 4 million deaths annually on earth. Fossil fuels are in use for a long time and this amount of usage wreak climate change thus overaccumulation of greenhouse gases and particles.

Wars are usually started to seize energy sources since Industrial Evolution. Starting from 2030, energy needs will increase 45%, parallel with population. Unfortunately, we consume 50% more than earth can handle. And now, more than ever, a sustainable civilization is possible. And furthermore, it is essential.

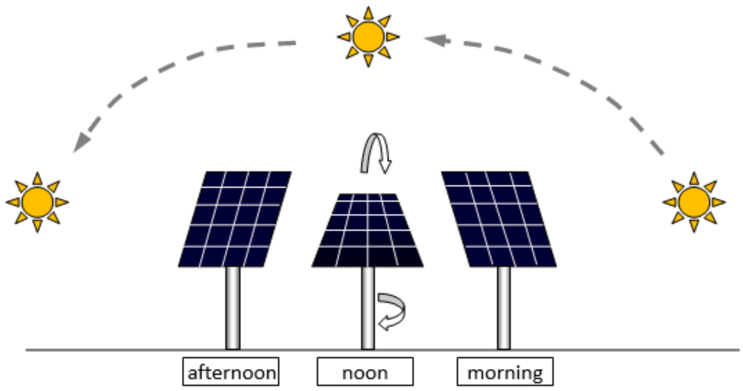

Figure 1.1 Two-axis solar tracker

Electrical energy is the most used type of energy in our daily life and there are many methods to produce electrical energy as from hydroelectric, nuclear, thermal and geothermal power plants, sun and wind. Ten thousand times more energy than the world needs can be obtained from the Sun. Sustainable energy and environment is possible with solar energy systems as the Sun has limitless energy. And our country Turkey, has an advantage on solar energy potential due to geographical location. Considering implementing solar trackers which orients a group of photovoltaic modules towards the Sun from sunrise to sunset, other energy sources will not be needed in future (Figure 1.1).

In the scope of this thesis, modular city plans have been examined and analyzed in terms of energy production and an energy plan has been proposed for the referred city plan. Sun tracker designs have been observed and a unique window shutter system has been designed to achieve modern cities' high design expectations, for especially south-faced areas such as Karsiyaka, Izmir. A dual-axis sun tracker has been designed and produced to observe the importance of PID control in position control and the results were discussed within the thesis. Then, global solar radiation has been collected in the research area and solar radiation estimation models have been discussed for the area then improved by developing new estimation models for the research area, Dokuz Eylul University Tinaztepe campus, for more accurate results to be used to evaluate produced energy. Sun trackers and control techniques have been studied and a new approach as in control technique has been studied and an active tracking system combined with chronological tracking method using a mathematical model to improve continues controllers was proposed for more efficient and reliable position control for sun tracking mechanisms. Position control of a DC motor has been modelled with a closed-loop control system and PID controller and analyzed in MATLAB. Different modifications of Ziegler-Nichols method have been applied and compared and step response characteristics of the system have been presented to performance evaluation. The resultant thesis is predicted to be used in future studies in the subjects of solar energy and sun tracker system projects for the research area and elsewhere with similar climatic conditions.

CHAPTER TWO
SOLAR ENERGY IN MODULAR CITY

Solar energy systems produce clean and sustainable energy. Solar energy potential of Turkey considerably high as it is shown in Figure 2.1. Izmir has 1,500 – 1,800 kWh/m^2 annual average solar radiation as Turkey’s annual average solar radiation is between 1,100 – 1,600 kWh/m^2.

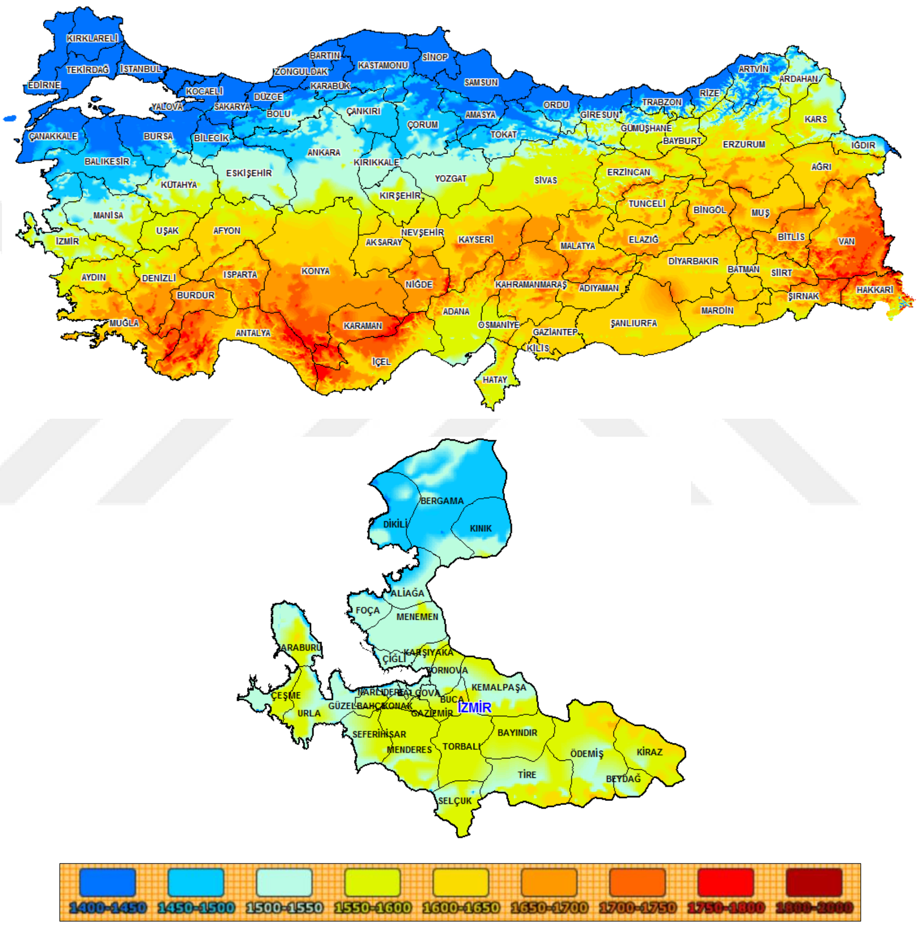

Figure 2.1 Solar energy potential atlas of Turkey and Izmir (YEGM, n.d.)

As our country has a high solar energy potential, examining and analyzing solar data is substantial to enhance and popularize the use of solar power. Within the context of this thesis, a setup of DC-voltage data logger with a pyranometer implemented on a prefabric inside Dokuz Eylul University campus area and collected voltage data. The recorded data analyzed with statistical methods to convert the data to global solar radiation. Global solar radiation can be used to estimate the total solar energy production for a location. Also, there are mathematical models to estimate the solar energy production (Vecan, 2011). In this research, it has been concluded that these previously generated models were not precise for our location. Thus, within the scope of this research, a new mathematical model for estimating the global solar radiation has been developed.

Power generation by renewable energy resources have been increasing and their share in power production predicted to be rise from 21% in 2012 to 33% in 2040 (Quesada et al., 2015). Although implementing solar systems with technology is overly expensive, many researches have focused on maximizing the efficiency and minimizing the cost (Ismail, Moghavvemi & Mahlia, 2013).

Solar power can be used to generate electric power through photovoltaics by either fixed or tracking systems (Quesada et al., 2015). Solar tracking systems are designed to kept the system steady at sun rays, to provide the output voltage around the highest power can be produced, and to provide efficient storage methods with control techniques (Yılmaz et al., 2015). Sun trackers are advanced alternatives to stationary photovoltaic panels by virtue of less efficiency in production when sun is not in an optimal angle. It has been proved by many researchers. Comparing one-axis and two-axis sun trackers, produced energy increases up to 100% depending on seasonal and geographical conditions (Mousazadeh et al., 2009). In Italy, one-axis and two-axis solar systems have been observed for 30 days and the efficiency of sun tracker observed as 12-20% higher than the fixed solar panel (Lazaroiu, Longo, Roscia & Pagano, 2015). Also Eke and Senturk obtained 30.79% more electricity from double-axis sun tracker compared to a latitude tilt fixed photovoltaics through one year in Mugla University campus (Eke & Senturk, 2012).

Producing clean and sustainable energy can lead to a sustainable civilization. Future villages and settlements are predicted to be modular. Based on this, energy problems may be solved by micro methods, not macro. The Venus Project is a leading example of that. Future settlements are tending to be modular just like the Venus Project, Ideal

Republic Village project from Ataturk era and Ildefons Cerda's Eixample in Barcelona. The common aim of these projects is to create a contemporary and environmentally friendly settlements. Within the scope of this thesis, these city plans have been analyzed in energy perspective and an energy plan has been developed. For urban regions, eye-pleasing solar system designs have been created.

2.1 Modular City Plans and Energy

2.1.1 Ildefons Cerda's City Plan, Barcelona

Ildefons Cerda was a civil engineering who left his job to be an urban planner. He planned a block structure obtaining residents and green spaces (Figure 2.2). Then it

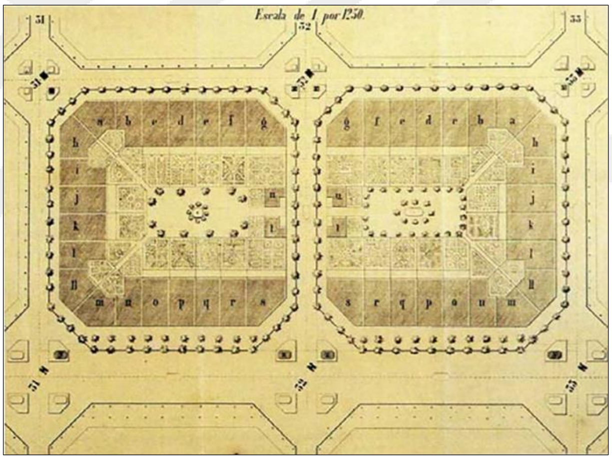

Figure 2.2 Cerda's modular city plan (Failed Architecture, 2014)

become as the known grid-based city, Eixample Barcelona, at the end of 19^{th} century (Figure 2.3). The planned city involves shops, services, markets and schools, larger institutions such as hospitals, cemeteries, parks, plazas and industrial buildings.

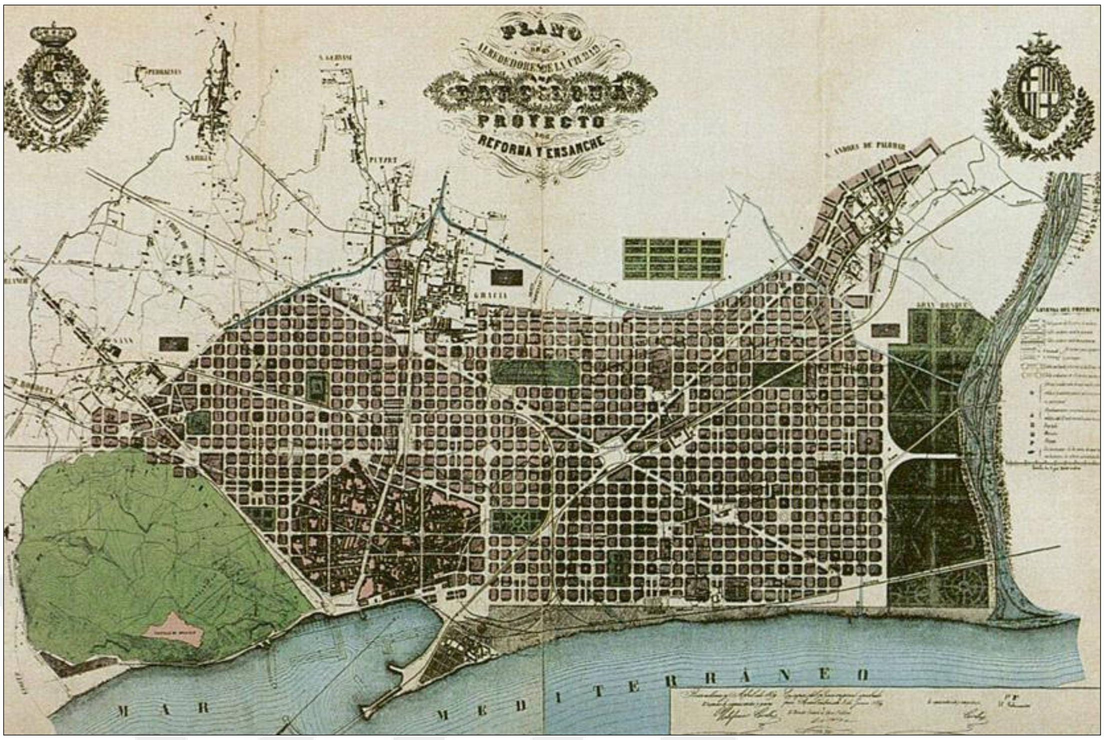

Figure 2.3 Cerda’s original Eixample Master Plan for Barcelona (Metropolitan Barcelona, 2011)

2.1.2 Venus Project

The Venus Project is an organization found by the architecture Jacque Fresco. Project aims a money-based nationalistic economy replaced with resource-based economy which is in harmony with human source, technology and environment. Founders believe this project will reduce poverty, hunger, homelessness, crime and other common world problems. Because in time, people will not require money to buy needs. So, they planned a world with automation replaced human labor, renewable energy and sustainable environment. And they aim a peaceful society.

Venus Project is a circular city including intelligent settlements, environment-friendly transportation, advanced technology, industrial factories that redesigned clean and energy efficient (Figure 2.4).

Figure 2.4 The Venus Project circular city (Overblog, 2016)

The Venus Project aims a self-sustained city as in energy. Energy is provided by solar, wind, wave, tidal, geothermal, hydroelectric, thorium and osmotic energy. Solar power can be produced by photovoltaics and concentrated solar power.

2.1.3 Ideal Republic Village Project

After Turkish War of Independence, national development was a big issue. Reconstructing the economy, making country resources efficient again, improving the education and most important of all, rebuilding cities and villages were significant in Mustafa Kemal Ataturk's perspective. The villages are the settlements where the national culture, customs and traditions, which must be established as the basis of the society, are lived and preserved. This project was drawn in 1937 and given to Afet Inan, Ataturk's spiritual daughter, by General Inspector of Thrace, General Kazim Dirik (Figure 2.5). The architecture's name is still unknown (Atabeyoglu, 2017).

Village is designed in a circular layout and radial axes. Design obtains, from the inside out, village square and institutional buildings in the center, next circle as residential district and then rural area. It was planned as 140 residents and 44 institutional buildings which contain elements of education, social, religious and cultural life, production, recreation, livestock, agriculture, health, storage, sales and management which may be needed in a village.

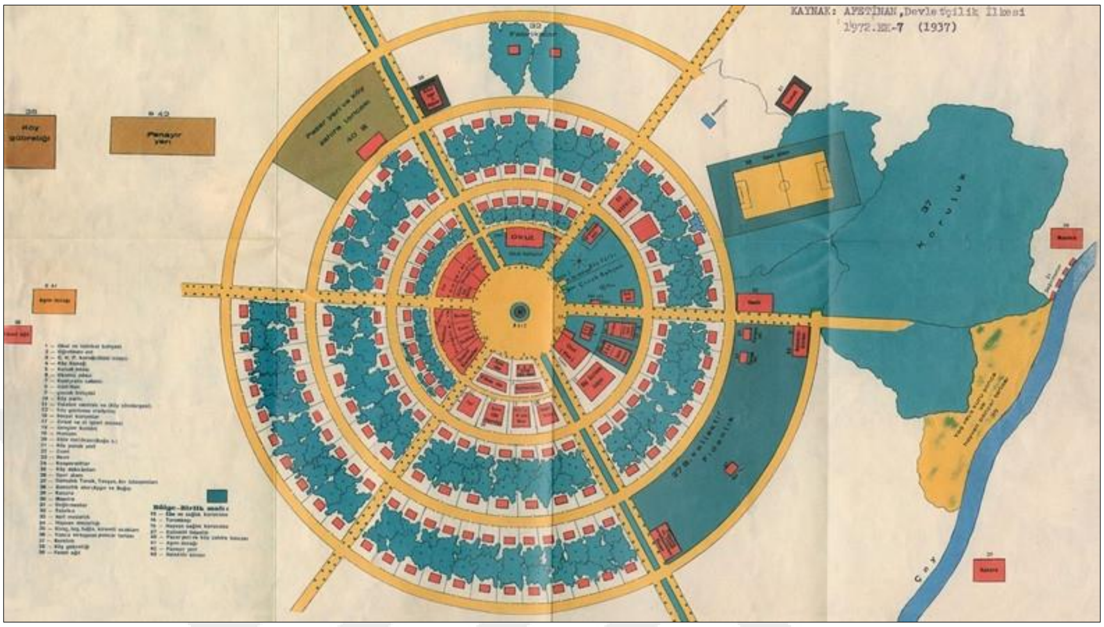

Figure 2.5 Ideal Republic Village plan (Teyit,2019)

The idea of combining the village and urban life forms, balancing industrialization to the village, urbanizing the village and giving a healthy form to urbanization has been discussed for many years. In the Republic of Turkey, the Prime Minister Bulent Ecevit put forward the concept of village-township project. In the late 1970s, the first applications of village-city projects in our country initiated in Van-Ozalp and Mudurnu-Taskesti, but not in the political conjuncture of time. Then in 2000, the project was held in Ordu-Mesudiye including 9 villages as Cavdar, Ilısar, Cardakli, Dayili, Esatli, Yuvali, Turkkoyu, Göcbeyi and Kıslacik (Basibuyuk, 2004).

Cavdar was the center of the plan (Figure 2.6). Investments related to basic infrastructure services include village roads, drinking water, sewage, irrigation, village mansions, communication; investments in education, health and social services including school and health center, sports facility, children's playgrounds, religious institutions, security and environmental regulation. Investments in economic and rural development are composed of the establishment of Village-Township Agricultural

Credit Cooperative, forest products integrated plant, livestock, crop production, forestry, trade and tourism investments.

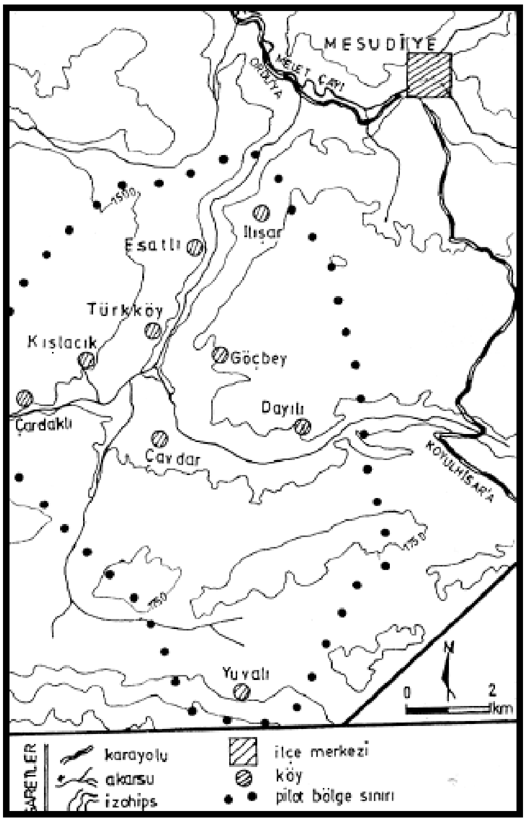

Figure 2.6 Map of the village-township area in Mesudiye (Basibuyuk, 2004)

Even though this project was ahead of its time, there is a missing part: energy. Interconnected electricity grid does not provide efficiency in the villages. At this point, renewable energy should be considered. Residents usually stay at these villages except winter and they heat water mostly through sun. So, solar energy would be a good choice for the residents.

Within the framework of the project, industrial plants are necessities in case of development and livelihood specially to prevent immigration to city centers. Every city project diminishes with immigration. There were two factories in Ataturk's village project.

Let's assume one is a textile factory and one is a food-packing factory. A textile factory producing plain/patternless fabric and dyeing them with 65 workers would consume 1,210,000 kWh energy monthly (Onoz, 2008), which is 3.315,069 kWh daily. If 80 W solar panels are chosen, 4,144 solar panels would be enough especially in summer days. 0.99456 acres of lands would be enough for installing 60 cm x 40 cm solar cells.

Yucemak Gida San. Tic. Ltd. Sti., a dry-food packaging factory, with 100 workers would consume 11,667 kWh energy monthly, 388.9 kWh daily according to a source. Again, with the same panel choice, 487 solar panels needed and 0.11688 acres of land is enough to install.

Solar panels can be installed to the sports facility, as in this project, to the football facility. Total facility size could be 156 m x 105 m for a 105 m x 68 m field. By using only the outer area, 15,092 solar panels can be installed. With 8.45 daily average sun hours thus 676 Wh energy production daily, this number of solar panels can produce 10,202 kWh energy per day. A household consumes maximum 8 kWh energy daily according to researches made by TEIAS. So, 15,092 panels can produce energy for 812 houses plus the mentioned two factories. Researches showed that solar trackers are at least 30% more efficient then stationary solar panels (Singh, 2018). That means with solar trackers, the produced energy, excluding factories energy, would be enough up to 1,055 households. The village-township project contains 144 residences only. If these residences are single-family detached homes, extra energy might be used in school, hospital and other facilities.

The present city structure is different from ideal modular city plans. And this present city structure requires particular solutions. At this point, integrating sun trackers would be more efficient and feasible.

These particular solutions might be applicable in Izmir, Karsiyaka. Residences are faced to south in this area and this is the most sunlight-received side. Solar panels can be implemented to shutters beside roof tops so that the produced energy satisfies the required energy.

2.2 Solar trackers

Solar tracking systems have been studied since McFee (1975) took a leading part in 1975 with the first active tracking system (Hafez, Yousef & Harag, 2018).

Dual-axis tracking system using azimuth and elevation angles with four electric-optical sensors assembled in 1984 by Zogbi & Laplaze (Zogbi & Laplaze, 1984). System compared sensor results and tracked the sun via two tracking motors. In 1986, Rumala (1986) applied four photoresistors under North-South and East-West placed cylinders and used closed loop control with shadow method. Then in 1996, a single-axis tracking system with three LDR that detects the focus state with one and detects the shadow and day-night information with other two was introduced by Kalogirou (1996).

Khalifa & Al-Mutawalli (1998) presented dual-axis solar tracking system that tracks sun every 3-min in horizontal, 4-min in vertical plane.

An American company Zomewords developed passive tracking systems and Poulek (1994) developed another using shape memory alloy (SMA) based on axis actuators.

There are many researches and studies about solar tracking systems to adjust modern cities and as a result, there are so many types and designs. Mainly, there are two types of tracking as single-axis and dual-axis and also many special types inspired from these two. In terms of tracking technologies; systems are mostly classified as active, passive, semi-passive, manual, and chronological (Hafez et al., 2018).

Figure 2.7 Smartflower (SmartFlower, n.d.)

To achieve modern city plan and design expectations, various designs of solar tracking systems have been presented and Smartflower is a prominent one. Smartflower is a solar tracker inspired from sunflowers (Figure 2.7). It was founded in Austria then acquired in 2018 by Energy Management Inc., a USA based company.

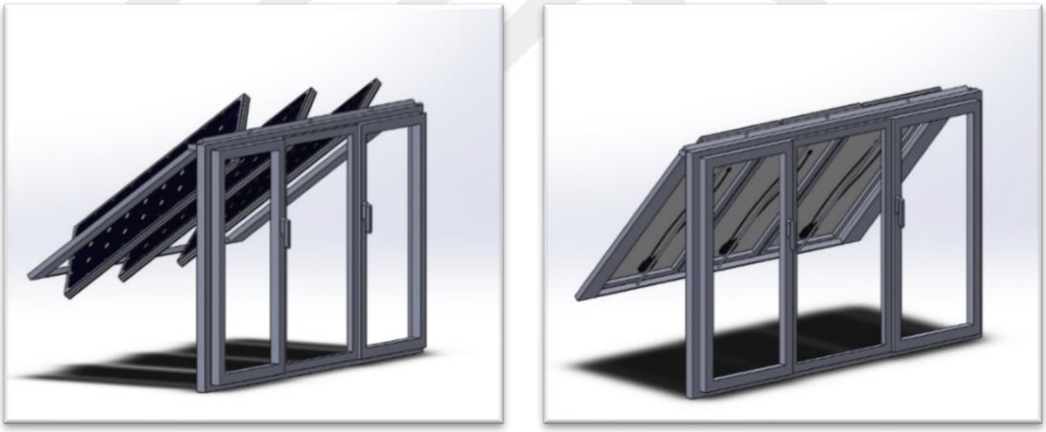

Figure 2.8 Design of window shutter solar tracker

In scope of this research, a specific design has been developed for Karsiyaka, Izmir (Figure 2.8). It is a solar tracker for window shutters. It can stay at an optimal angle or track sunlight. It would be more efficient if placed toward south so it can track the sun from sun rise to sun set.

CHAPTER THREE
MODELLING AND MATERIALS

The basis of experimental set-up is an experimental model that was studied in Mechanical Engineering Automatic Control Laboratory by Ismatli in 2017. Light dependent resistors (LDR) are commonly used to direct photovoltaic modules to sunrays as in this set-up with controllers, motor and PV system (Figure 3.1). LDR outputs are compared and the outcome signal is the reference to the controller (Ismatli & Goren, 2017).

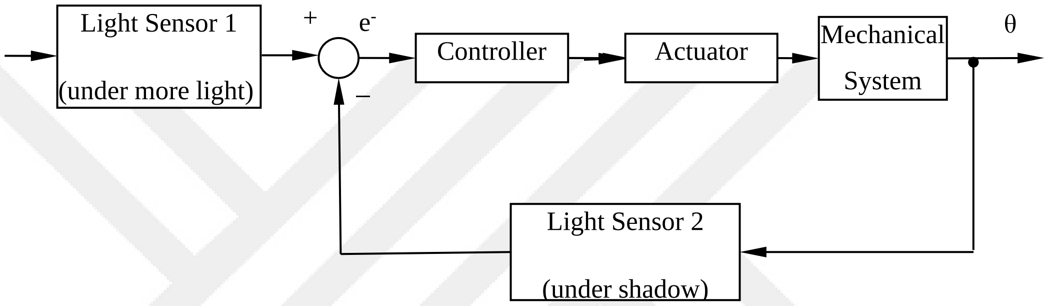

Figure 3.1 Control block diagram of angular position control with LDR

Nevertheless, this control system would not be efficient in cloudy days that sensors may not be able to estimate the location of sun (Ferdaus, Mohammed, Rahman, Salehin & Abdul Mannan, 2014). Due to low solar radiation difference between sensors, system may not be able to make the right decision (Hafez et al., 2018).

As an outcome of low solar radiation, produced energy may not overcome the energy consumed by the tracking system. If the controller estimates the global solar radiation with mathematical models for each day and also measures the instantaneous radiation value to estimate energy production, system can decide to rotate the PV module or stay at a constant angle for the day according to efficiency. In this study, an active tracking system is combined with chronological tracking method using a mathematical model in order to improve the robustness of continuous controllers for sun trackers. Optimal angle for a solar panel is the angle that the sun lights can fall on the panel with steep angle. And this angle is dependent on the latitude and the location of the implementation area (Karafil, Ozbay, Kesler & Parmaksiz, 2015). The angle between the horizontal plane and the panels is the tilt angle (β) and varies between 0 to 180 degrees. The tilt angle of the plane for east-west rotation axis is calculated by Equation 3.1.

$$\beta = |\phi - \delta| \tag{3.1}$$

$$\delta = 23.45 \sin\left(360 \frac{284 + n}{365}\right) \tag{3.2}$$

ϕ, latitude of the area, is 38.370912° for Tinaztepe and δ is the solar declination (Equation 3.2). Solar declination is dependent on the day of the year which means the tilt angle is also dependent. The monthly average tilt angles for Tinaztepe campus area are calculated using daily data and shown in Table 3.1. According to the seasons, the trajectory of the sun is closer to the ground on the horizontal axis in winter and autumn; slightly steeper in spring and almost parallel to horizontal in summer.

Table 3.1 Monthly average tilt angles (°)

January	**February**	**March**	**April**	**May**	**June**
59.2181	46.6933	40.7601	27.9462	19.5651	14.8005
July	**August**	**September**	**October**	**November**	**December**
17.2694	25.0749	35.2039	48.2195	55.5691	59.4840

In Figure 3.2, Controller 1 calculates the tilt angles for day and hour and instantaneous energy generation with measured instantaneous radiation value to decide whether staying at a constant angle or switching to active sun tracking mode. Controller 2 controls the position with angles from Controller 1 and output of the position sensor. The mechanical system that involves photovoltaics, panel and gearbox operated by actuators.

Figure 3.3 shows storage and consumption process of the produced electricity of a sun tracker. The produced energy would be stored in the battery to be used or it would be consumed by the motor in need.

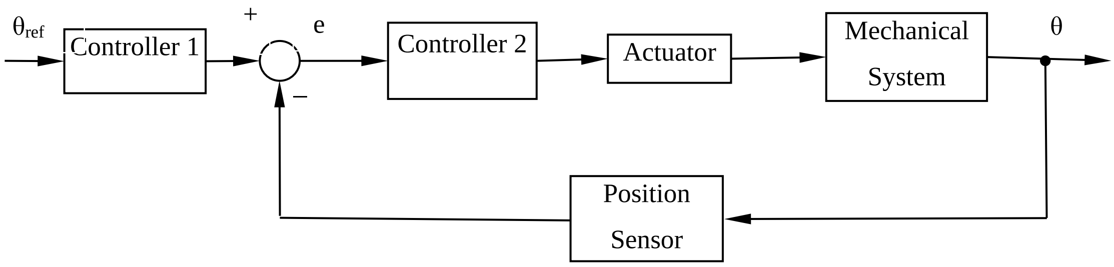

Figure 3.2 Control block diagram of angular position control of chronological tracker

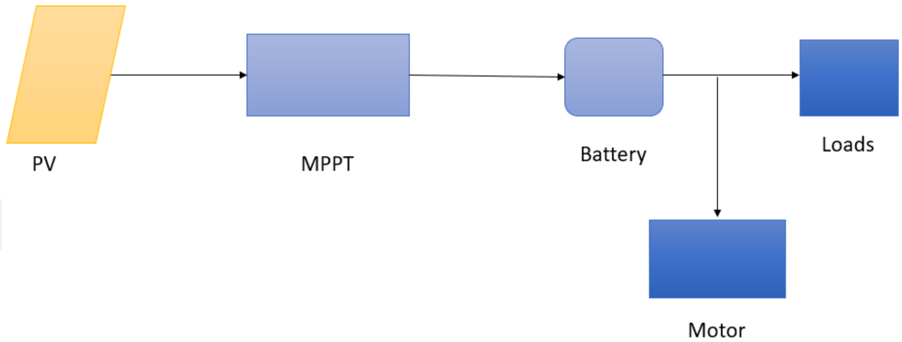

Figure 3.3 Electrical connections of the solar tracker

3.1 Components of Solar Trackers

Solar cell is a tool that converts light directly into electric current. The solar cell, working as a semiconductor diode, converts the energy of sunlight directly into electrical energy by utilizing the internal photoelectric reaction (Koussa, Haddadi, Saheb, Malek & Hadji, 2012). Figure 5 describes solar cell's equivalent electrical circuit (Ismatli & Goren, 2017). I_{ph} is the generated current, V_{pv} is the generated voltage, R_s is equal to the resistance of the semiconductor material forming the cell and the sum of the contact resistances that occur at the connection points of the cells, R_p is sum of the resistances formed between the layers and around the cells in the thin film structure consisting of very thin layers.

Equation 3.3 represents the amount of current to the external circuit according to single diode model as K (Boltzmann constant) is $1.38*10^{-23}$ J/K. T_c is absolute temperature (K), q is electron charge, V is voltage on the battery and I_0 is dark saturation current that varies greatly depending on temperature. The resistances, R_p and R_s, are neglected for the single diode equivalent for the ideal solar cell.

$$I = I_{ph} - I_0 \left[\exp\left(\frac{qV}{kT_c} \right) - 1 \right] \tag{3.3}$$

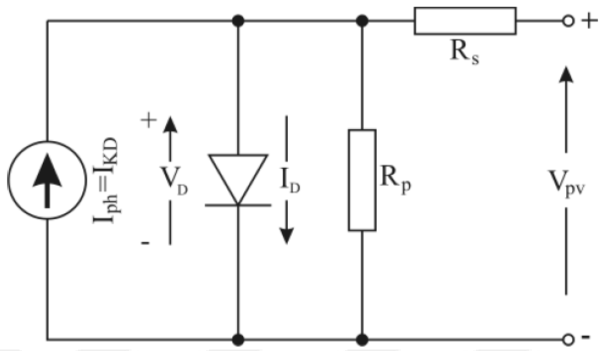

Figure 3.4 A solar cell

Light dependent resistors (LDR) are elements that vary in resistance to the light intensity falling on them. It is a passive electronic component and assumed as a linear component. As the light falling on it increases, the resistance value decreases non-linearly. LDR's resistance is minimum in the light, maximum in the dark. It has the same features in both AC circuit and DC circuit.

Direct current (DC) motors convert electrical energy to mechanical energy in the form of rotation of the rotor. Figure 3.5 demonstrates a simple DC motor model (Sahputro, Fadilah, Wicaksono & Yusivar, 2017).

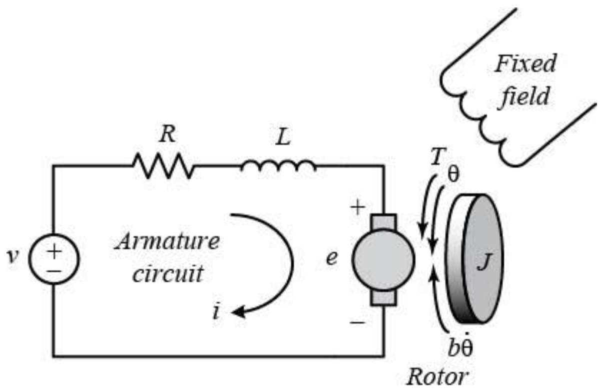

Figure 3.5 Schematic diagram for electrical drive system

Position control of a dc motor with potentiometer is shown in Figure 3.6. System has one feedback control; a velocity feedback as back electromotive force gain. θ_s is actual displacement and θ_d is the desired displacement.

T_m, the motor torque, is proportional to the armature current (i_a), and torque constant (Ki):

$$T_m = K_i i_a \tag{3.4}$$

The back EMF is represented as V_b(t) and related to the back EMF constant (K_b) and angular velocity (ω_m) as shown in Equation 3.5. Using D'Alambert's principle, Equation 3.6 is obtained where K_θ (Kt) is the conversion constant, n is gear ratio, L and R is inductance in Henries and resistance in ohms of the motor armature winding.

$$V_b = K_b \omega_m \tag{3.5}$$

$$J\frac{d\theta}{dt^2} + B\frac{d\theta}{dt} = K_i i_a \tag{3.6}$$

The closed-loop transfer function is expressed in Equation 3.7 for position control of a dc motor and the block diagram built with MatLab is shown in Figure 3.6.

$$\frac{\theta_s(s)}{\theta_d(s)} = \frac{nK_\theta K_i}{s^3LJ + s^2(Lb + RJ) + s(Rb + K_iK_b) + nK_\theta K_i} \tag{3.7}$$

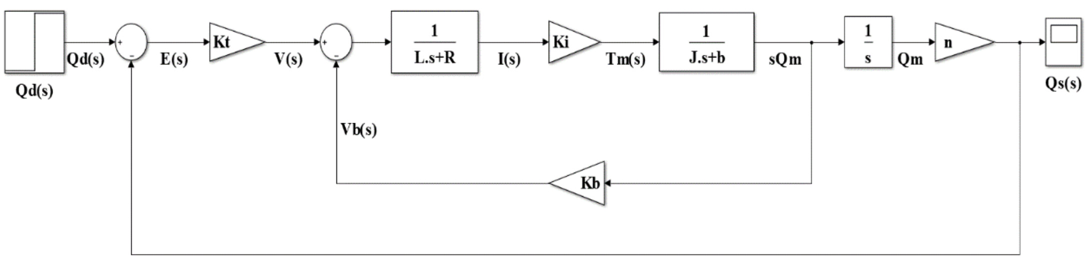

Figure 3.6 Position control of a dc motor

Maximum power point trackers (MPPT) used to increase usage and storage efficiency of generated power. MPPTs are DC-DC converter units and they are more effective when the system is under changing radiation. The generated voltage of PV modules can vary between an interval and boost converters increases the input voltage to a higher output voltage (Sivakumar, Jagabar Sathik, Manoj & Sundararajan, 2016).

There are simply three basic topologies of MPPT as boost converter, buck converter and buck-boost converter. Buck-boost type converter is chosen for this study. Erdogan examined different topologies and choose boost type converter to study stabilizing the output voltage (Erdogan, Dincler, Kuncan, Ertunc & 2014). Figure 3.7 shows how buck-boost converters work.

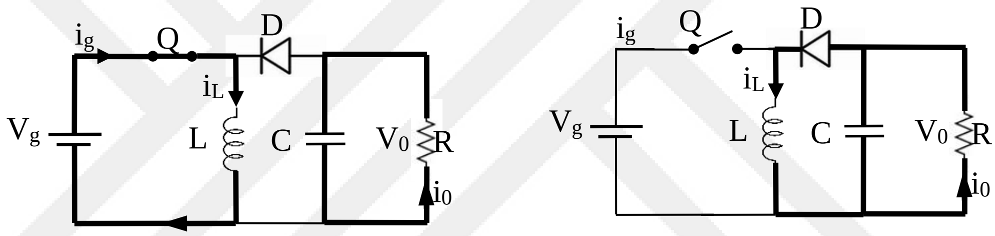

Figure 3.7 Buck-boost converters

As it is shown in Figure 3.7; Q switch determines the current direction and path. Diode is in transmission when Q switch is on and is affected by reverse voltage. When the switch is off, the current flows through C, D and the load (Caliskan, Unal & Orhan, 2017). Output of the voltage is expressed in Equation 3.8 for ideal circumstances. d varies between 0 and 1. While d is smaller than 0.5; it is buck converter. Otherwise it is a boost converter.

$$V_0 = \frac{d}{1-d} V_g \tag{3.8}$$

Energy storage is an important issue and the batteries are almost the most important component for PV modules. Lead acid batteries are used in solar or hybrid systems for low costs and more storage compared to nickel or lithium batteries (Armenta, 2002).

However, lithium batteries are more common to store more energy in less volume or mass.

$$U_{bat} = E_{th} \pm I_{bat} R_{bat} \tag{3.9}$$

In Figure 3.8, a battery model can be seen. E_{th} (V_0) is the open circuit voltage, R_{bat} is the internal resistance of the battery, U_{bat} is the voltage of the battery and I_{bat} is the current of the battery. For lead-acid batteries, charging process can be modelled using Equation 3.9 (Goren, 2017). I_{bat} is positive during charge whereas it is negative during discharge.

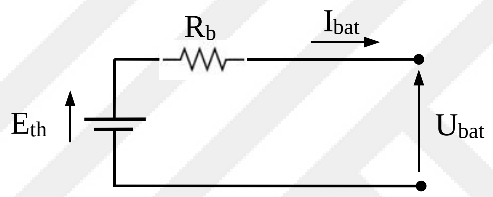

Figure 3.8 Battery model

3.2 Solar Radiation Estimation Model for Tinaztepe, Izmir

Global solar radiation can be estimated with mathematical models or simply recording voltage data with data logger and pyranometer. The accuracy of mathematical models examined in this section.

EKO MS-140 first class pyranometer and Hioki LR5041 compact DC voltage data logger is used to collect solar radiation data. Pyranometers are a type of actinometer used for routine global solar irradiance measurements on a planar surface and it is designed to measure the solar radiation flux density from the hemisphere above within a wavelength range 0.3 μm to 3 μm. This is a thermopile type pyranometer which converts thermal energy into electrical energy by consuming radiation from sun through highly-absorbing black paint that is placed into double-coated hemispheric glass.

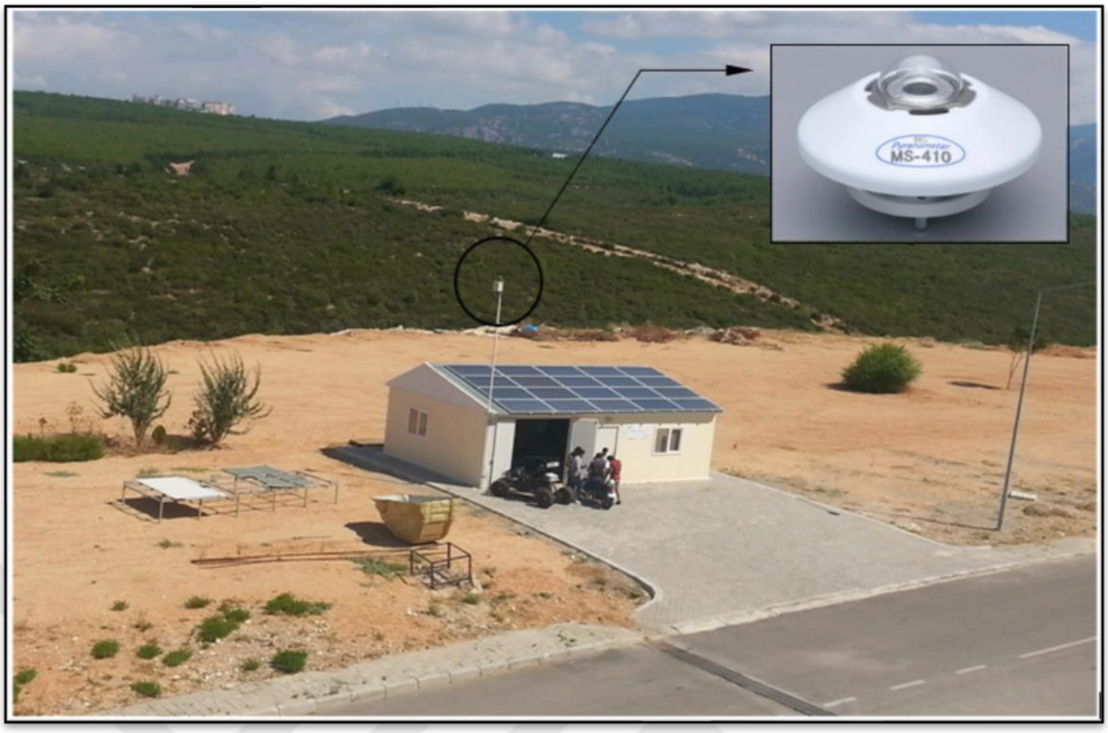

Figure 3.9 Location of the setup (Personal archive, 2014)

Global solar radiation data is collected with pyranometer that is mounted on the DECharge workshop building roof in Dokuz Eylul University Tinaztepe location 38°22'15.3"N 27°12'28.5"E. The pyranometer is shown in Figure 3.9. Compact DC voltage data logger has ±0.5 %rdg. ±5 dgt. accuracy and recorded data with 5, 10 or 15 minutes time intervals. Data of April 2018, May 2018, June 2018, July 2018, August 2018, September 2018, October 2018, November 2018, December 2018, January 2019, February 2019 and March 2019 have been recorded and the data processed with a calibration constant of 7.729 $\mu V/Wm^2$ (Appendix 1).

There are many mathematical models to estimate global solar radiation. There are researches for accurate mathematical models of Turkey and Aegean region in the literature and one of the most accurate is studied in Vecan's thesis and developed by Ulgen & Hepbasli (Vecan, 2011). Equation 3.10 is developed by Ulgen & Hepbasli to estimate monthly-average daily radiation on a horizontal surface (H) depending on sunshine duration. Equations 3.11 and 3.12 are from the same study and these are also for Izmir region. These mathematical models were developed by using Equation 3.19, quadratic correlation between H/H_0 and S/S_0 (Ögelman, Ecevit & Tasdemiroglu, 1984).

$$H = H_0 \left[0.2408 + 0.3625 \left(\frac{S}{S_0} \right) + 0.4597 \left(\frac{S}{S_0} \right)^2 - 0.3708 \left(\frac{S}{S_0} \right)^3 \right] \tag{3.10}$$

$$H = H_0 \left[0.263 + 0.512 \left(\frac{S}{S_0} \right) \right] \tag{3.11}$$

$$H = H_0 \left[0.238 + 0.610 \left(\frac{S}{S_0} \right) - 0.085 \left(\frac{S}{S_0} \right)^2 \right] \tag{3.12}$$

Equations 3.13-3.17 were used to estimate the monthly average daily radiation H (Yilmaz et al., 2015), (İbrahim, 2006).

$$H_0 = \frac{24}{\pi} G_0 \left(\cos\phi \cos\delta \sin w_0 + \frac{\pi}{180} w_0 \sin\phi \sin\delta \right) \tag{3.13}$$

$$G_0 = G_{sc} \left[1 + 0.033 \cos\left(\frac{360n}{365} \right) \right] \tag{3.14}$$

$$\delta = 23.45 \sin\left(360 \frac{284 + n}{365} \right) \tag{3.15}$$

$$\cos w_0 = -\tan\phi \tan\delta \tag{3.16}$$

$$S_0 = \frac{2}{15} \left[\cos^{-1}\left(-\tan\phi \tan\delta \right) \right] \tag{3.17}$$

$$H = H_0 \left[0.263 + 0.512 \left(\frac{S}{S_0} \right) \right] \tag{3.18}$$

H_0 is monthly average daily extraterrestrial radiation in W/m^2, S_0 is the monthly average of the maximum possible daily hours of bright sunshine (h), w_0 is sunset hour angle. ϕ is the latitude of the area and 38.370912° for Tinaztepe. G_{sc}, the solar constant is 1367 W/m^2. N is the day of the year starting from January 1st. S is the bright sunshine hours and shown in Table 3.2 for Izmir.

Table 3.2 Average of bright sunshine hours S (h)

January	**February**	**March**	**April**	**May**	**June**
3.10	4.46	6.45	6.63	8.82	10.41
July	**August**	**September**	**October**	**November**	**December**
12.01	10.25	9.13	7.49	4.9	3.52

The collected data of Tinaztepe campus area and results of mathematical models (Equations 3.10, 3.11, 3.12) were compared. The most accurate model was Ulgen & Hepbasli's but the results were not precise enough. That result evinced the need of a unique mathematical model for the research area. New and specific solar radiation estimation models for Tinaztepe campus area has been developed using MatLab as part of this research. Using the recorded data to develop new mathematical models made the new models more precise. There are four newly developed mathematical models for each season due to the difference of weather conditions between seasons that effects the accuracy and precision of daily global solar radiation estimation models and these mathematical models are based on previous models and recorded data.

$$H = H_0\left[a + b\left(\frac{S}{S_0}\right) + c\left(\frac{S}{S_0}\right)^2\right] \tag{3.19}$$

$$H = H_0\left[2.8687 - 7.5813\left(\frac{S}{S_0}\right) + 6.4552\left(\frac{S}{S_0}\right)^2\right] \tag{3.20}$$

$$H = H_0\left[-4.2154 + 12.0896\left(\frac{S}{S_0}\right) - 7.3359\left(\frac{S}{S_0}\right)^2\right] \tag{3.21}$$

$$H = H_0\left[1.937 - 5.2374\left(\frac{S}{S_0}\right) + 4.8923\left(\frac{S}{S_0}\right)^2\right] \tag{3.22}$$

$$H = H_0\left[5.25 - 26.7613\left(\frac{S}{S_0}\right) + 37.1236\left(\frac{S}{S_0}\right)^2\right] \tag{3.23}$$

Equation 3.20 is for spring months, Equation 3.21 is for summer months, Equation 3.22 is for autumn months and Equation 3.23 is for winter months and these are called

“Unver and Goren’s models” within this research (Unver & Goren, 2019). These mathematical models and their accuracies will be discussed within the next chapter.

CHAPTER FOUR

EXPERIMENTS AND PERFORMANCE EVALUATION

4.1 Solar Radiation Estimation Models

Collected solar radiation data of Tinaztepe and calculated solar radiation values of Unver and Goren's models and Ulgen and Hepbasli's model are compared for consecutive month for a year (April-December of 2018, January-March of 2019) and shown in Figure 4.1.

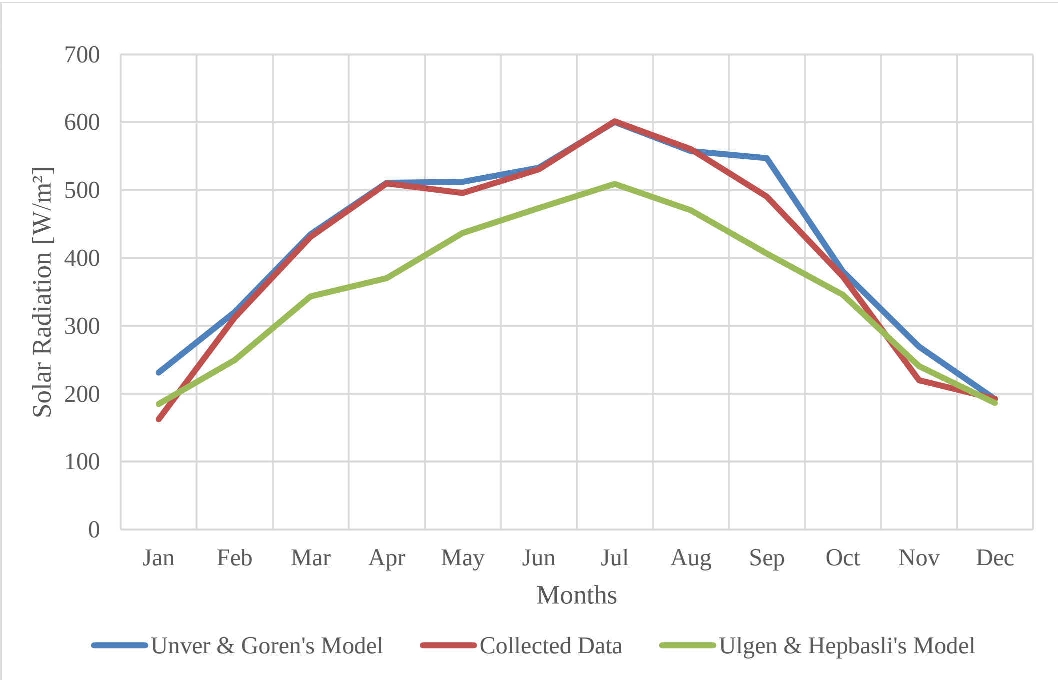

Figure 4.1 Comparing graphic of monthly average daily solar radiation

In Figure 4.1, it can be seen that Unver and Goren's seasonal models are more accurate monthly than Ulgen and Hepbasli's model, except January.

There are some methods to measure the magnitude of error. Root Mean Square Error (RMSE) is one of them. Respectively, RMSE is the standard deviation of prediction errors (residuals). It demonstrates how concentrated the data is around the line of best fit by measuring the average magnitude of the error as x_k is the measured value and y_k is the calculated value (Equation 4.1). RMSE method may give exaggerated results in case of large deviations as it squares errors.

$$RMSE = \sqrt{\sum_{k=0}^{n} (y_k - x_k)^2 / n} \tag{4.1}$$

When RMSE of the mathematical models have been calculated, it is obvious, and can be seen in Figure 4.2, that seasonal mathematical models have less error than Ulgen and Hepbasli's model for Tinaztepe campus area, except January. Nevertheless, January 2019 has lower solar radiation than predicted as it can be seen in Figure 4.1 and it is due to weather changes and so global warming. By collecting more data in the future for the research area, mathematical models would be more accurate in time.

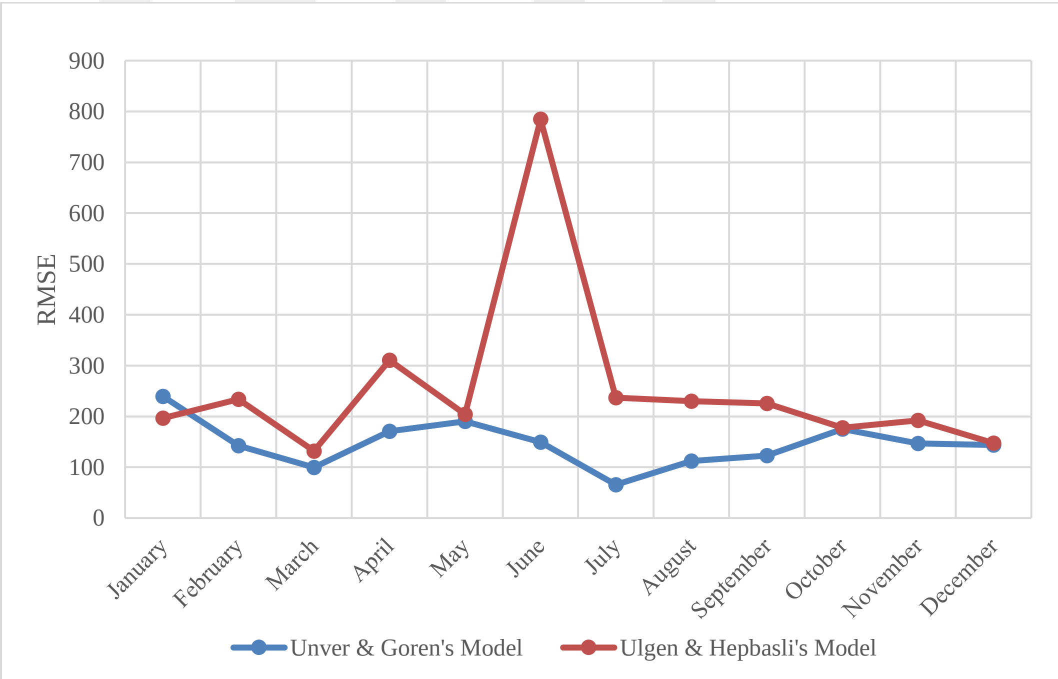

Figure 4.2 RMSE comparison

There are different resources to obtain solar radiation data such as websites. Photovoltaic Geographical Information System (PVGIS) is a European Commission project in European Commission Joint Research Centre at the JRC cite in Italy. The main focus of this project is dissemination of knowledge and data about solar radiation and PV performance. Online PVGIS application is one of the most common work of the project and allows researchers to access solar radiation data obtained from satellites and PV performance studies (Huld, Müller & Gambardella, 2012).

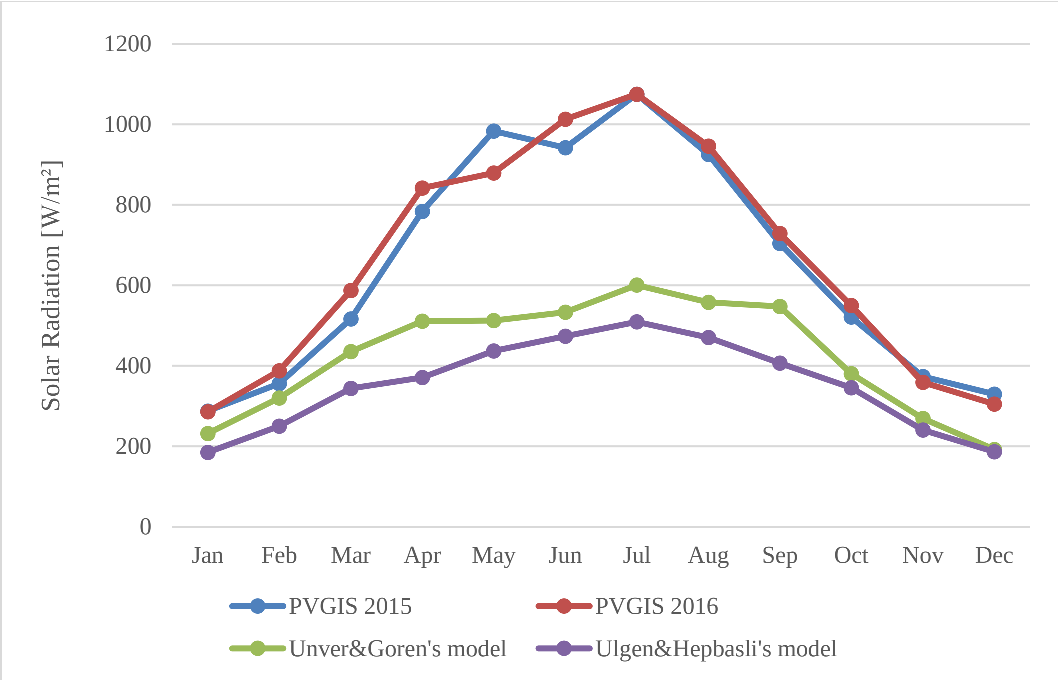

Figure 4.3 Comparison graph

2015 and 2016 monthly average daily solar radiation data of the research area were obtained from PVGIS online web application and compared in Figure 4.3 with mathematical models. Unver & Goren models have better accuracy than Ulgen & Hepbasli model as it can be deducted from the graph above. Unver & Goren models are much closer to PVGIS data curve for each month of the year.

4.2 Controller Design

The dynamic response of a system can be described by linear ordinary differential equations with constant coefficients and feedback control is necessary to modify the dynamic behavior of the system. System behavior can be insufficient so monitoring the system response to drive the system through desired response by generating a system input with feedback control is essential.

Speed and angle of the motor can be easily controlled with DC motors (Amiri & Bagheri, 2013). In this research, position control of a DC motor has been modelled with a closed-loop control system and analyzed in MatLab. PID controller is used to control the position of the motor and enhance it by constantly changing the control effect according to the magnitude of the error.

Table 4.1 Parameters of the DC motor

L	**R**	**K_I**	**J**
1.25 e^{-5} H	3.3333 Ω	0.2451 N.m/A	0.01 kg.m^2
b	**n**	**K_b**	**K_θ**
e^{-8} N.m/(rad/s)	1/297.92	0.3342 V.s/rad	6.876 e-4 N.m/A

Parameters of the chosen DC motor are shown in Table 4.1. The transfer function of the system is obtained and shown in the previous pages as Equation 3.7. and the transfer function of a PID controller is shown in Equation 4.2-4.3.

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s \tag{4.2}$$

$$G_c(s) = K_p \left(1 + \frac{1}{T_i s} + T_d s\right) \tag{4.3}$$

PID control coefficients can be obtained based on experimental and computational methods. Manual tuning methods can be time consuming; a heuristic method such as Ziegler-Nichols would be more effective. For this system, Ziegler-Nichols method is used to determine the critical gain (K_c), the integral time constant (T_i) and the derivative time constant (T_d). First, step input is used as reference. Then a constant gain K is used to control the closed-loop system. K is increased until system response has a continuous oscillation response, used as K_p, and then oscillation period (T_c) is obtained. Finally, the control system can be designed with following equations. Equation 4.4 is for P control; Equations 4.5 are for PI control and Equations 4.6 are for PID control.

$$K_p = 0.5K_c \tag{4.4}$$

$$K_p = 0.45K_c \quad T_i = 0.83T_c \tag{4.5}$$

$$K_p = 0.6K_c \quad T_i = 0.5T_c \quad T_d = 0.125T_c \tag{4.6}$$

K_c is the critical gain and can be determined by Routh-Hurwitz method and it is 317,243.493 for this model. T_c is 20.0101. In the following figures, comparison of change of control coefficients are shown. Figure 4.4 shows the step responses of the system with PID parameters determined with Routh-Hurwitz method.

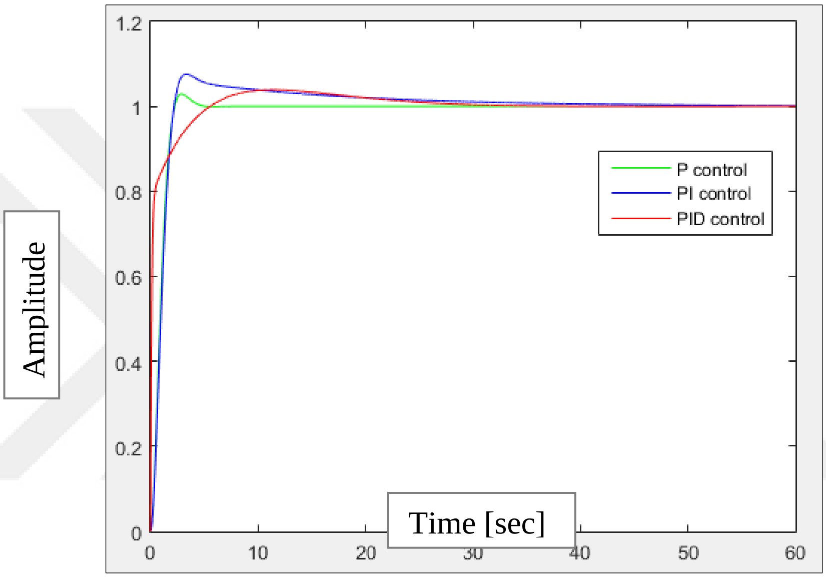

Figure 4.4 Step responses of the system with PID parameters

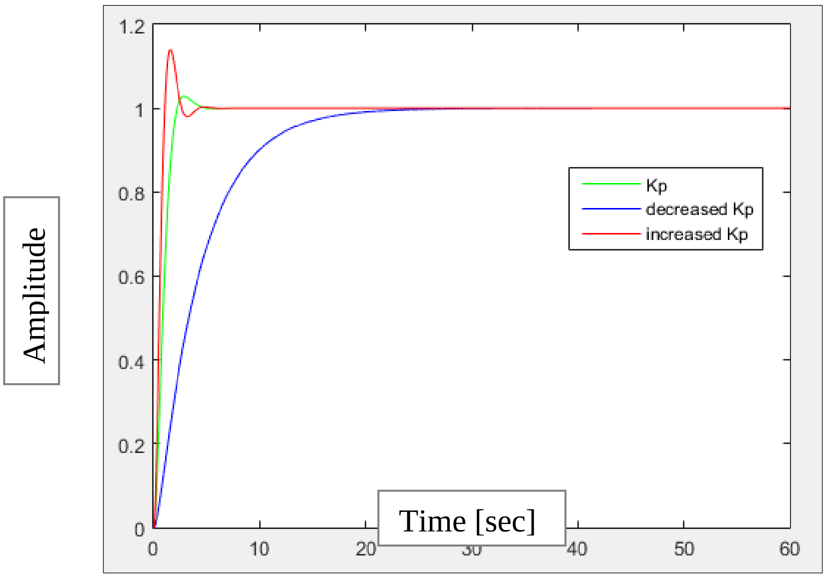

Figure 4.5 P control with different K_p parameters

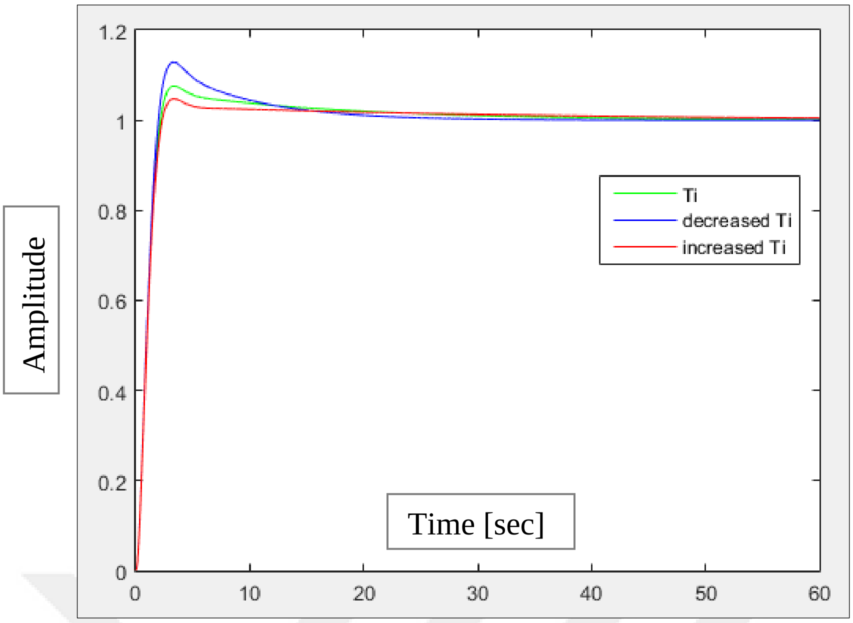

Figure 4.6 PI control with different K_i parameters

Figure 4.5 demonstrates the step responses of the system with proportional control and different K_p parameters. Figure 4.6 demonstrates the step responses of the system with proportional-integral control and different K_i parameters. Figure 4.7 demonstrates the step responses of the system with proportional-integral-derivative control and different K_d parameters.

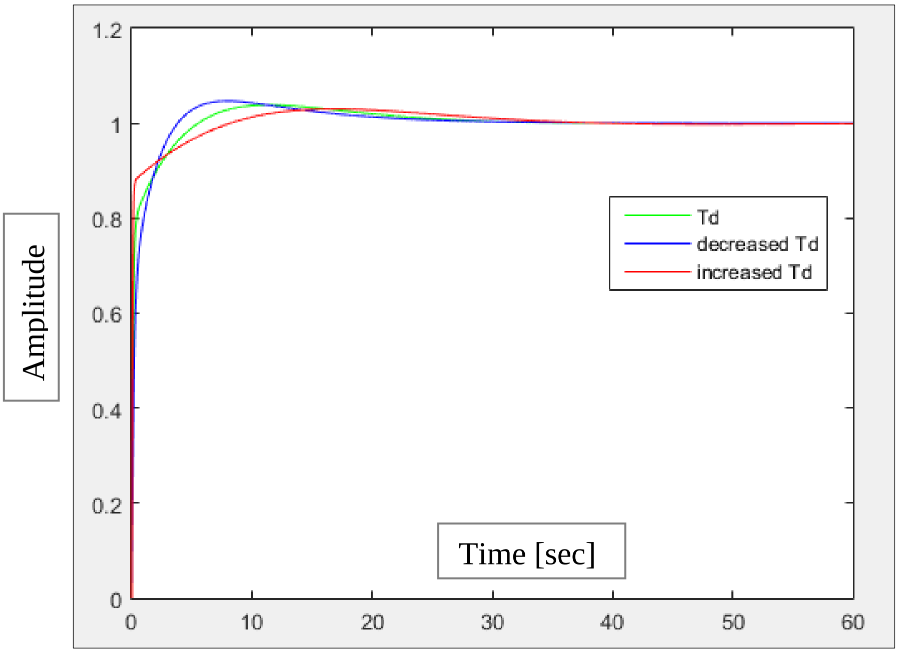

Figure 4.7 PID control with different K_d parameters

Table 4.2 Different Ziegler and Nichols modifications

#	Method	K_p	T_i	T_d
1	Ziegler-Nichols	$0.6K_c$	$0.5T_c$	$0.125T_c$
2	Pettit-Carr	K_c	$0.5T_c$	$0.125T_c$
3	Pettit-Carr	$0.67K_c$	T_c	$0.167T_c$
4	Pettit-Carr	$0.5K_c$	$1.5T_c$	$0.167T_c$
5	Chau	$0.33K_c$	$0.5T_c$	$0.333T_c$
6	Chau	$0.2K_c$	$0.55T_c$	$0.333T_c$
7	Bucz	$0.54K_c$	$0.79T_c$	$0.199T_c$
8	Bucz	$0.28K_c$	$1.44T_c$	$0.359T_c$

Ziegler-Nichols is an interesting research topic among scientists. Thus, there are more than forty modifications and some of them are shown in Table 4.2 (Bucz & Kozakova, 2018). Also, a PID controller tool is available at MatLab Simulink. All of the nine PID tuning methods were applied and compared in Figure 4.8.

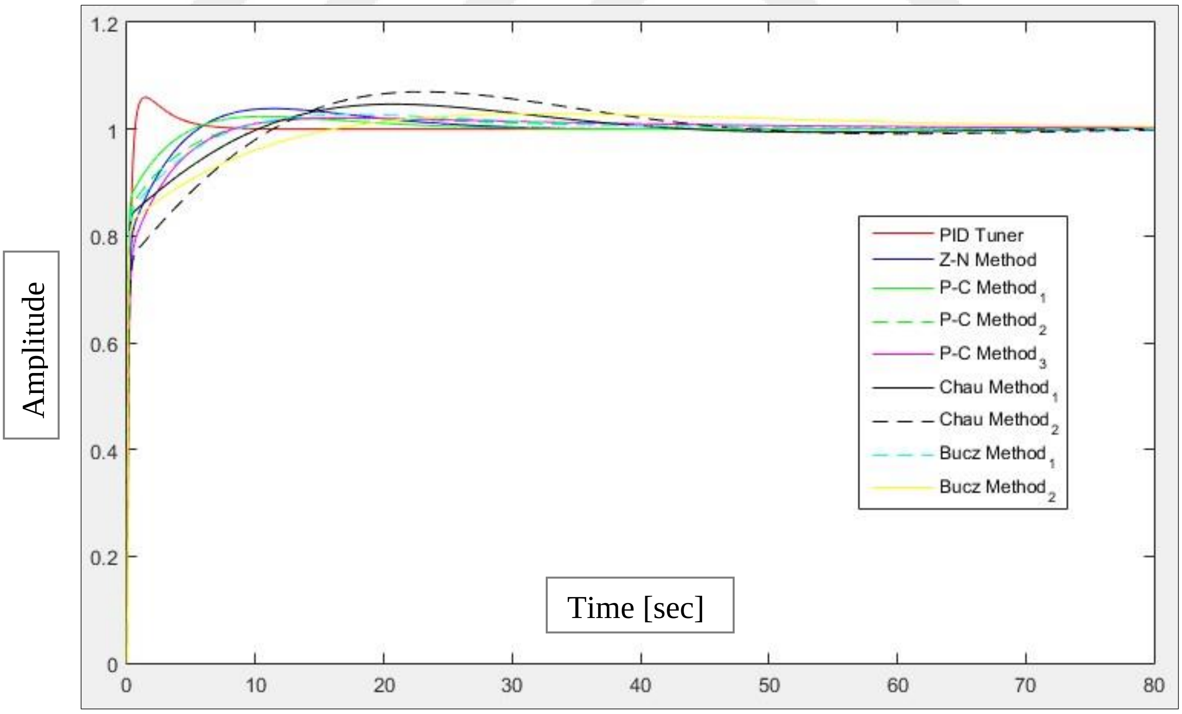

Figure 4.8 Comparison of various PID tuning methods

Step response characteristics of the system are listed in Table 4.3 for performance evaluation. Any of these methods can be chosen depending on the desired result.

Table 4.3 Response characteristics

Method	**Rise time [sec]**	**Settling time [sec]**	**Overshoot %**	**Peak point**	**Peak time [sec]**
PID tuner	0.3860	4.0642	5.9421	1.0594	1.4400
Ziegler-Nichols	2.0619	19.9268	3.8488	1.0385	11.3900
Pettit-Carr [1]	0.8643	14.4081	2.3759	1.0238	10.6700
Pettit-Carr [2]	1.6832	5.9592	1.9564	1.0200	16.7500
Pettit-Carr [3]	2.8553	6.4682	1.8660	1.0209	16.8100
Chau [1]	3.2867	33.7694	4.6393	1.0467	20.7500
Chau [2]	5.6981	40.9506	7.1660	1.0699	23.0100
Bucz [1]	2.1464	26.0710	2.7370	1.0273	17.5400
Bucz [2]	4.8740	42.8915	2.4192	1.0287	32.4300

4.3 Sun Tracker Set-up

A dual-axis sun tracker set-up was designed and produced in Mechanical Engineering Automatic Control Laboratory in collaboration with Mertcan Akin (Figure 4.9). The sun tracker is controlled with two DC motors, two potentiometers, four LDR sensors and a microprocessor to track the sun for maximum efficiency or stay at an optimal angle for one axis and track the sunlight at the other axis. PID control is used for position control and the control parameters are determined manually through experiment.

Four LDR sensors placed in each corner of the solar panel measure the light intensity and microprocessor processes its value, compares north-south and east-west differences to direct the panel towards maximum sunlight. In Appendix 2, orientation of the proposed two-axis sun tracker is shown as table. Table includes data of LDR’s in lux and tilt angles in degrees.

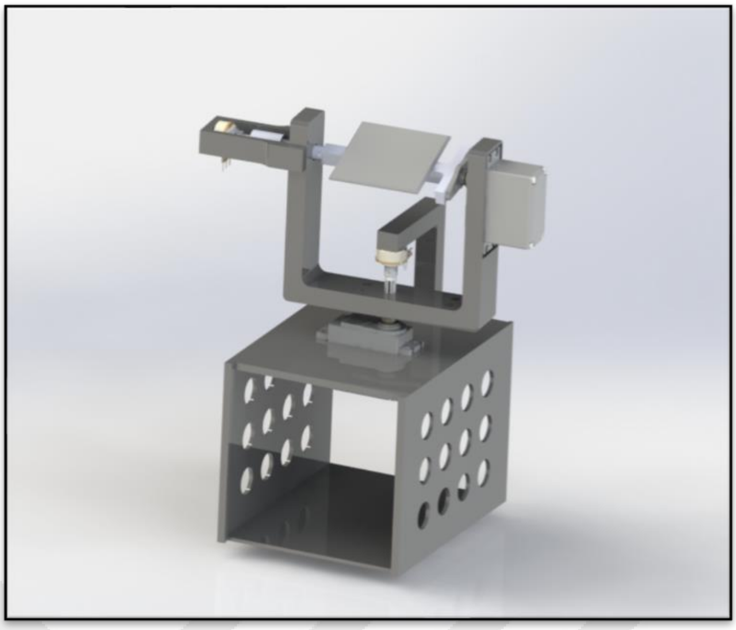

Figure 4.9 Sun tracker design

Light dependent resistors (LDR) are commonly used as light sensors. The amount of light falling on the LDR changes the resistance. And measuring the changing resistance and also knowing the characteristics of the LDR enables to evaluate the amount of lux falling on the LDR, the amount of power from the light falling on. So, the difference between these resistors determines the orientation of the mechanism. Appendix 2 demonstrates the determination of the angular position control. East and west lux difference determines the azimuth angle; north and west lux difference determines the tilt angle.

CHAPTER FIVE
CONCLUSION

This proposed study is mainly focused on the implementation of sun trackers. Modular city plans are examined and modernized with energy planning. The importance of the energy planning is underlined by estimating promising energy production and simulating the areas that can be used to plant solar panels. Application of modular city plans and the energy plans could prevent the immigration and help rural development. These city plans can also be implemented in urban areas. A unique design for window shutters is designed and presented within this research for the purpose of a more eye-pleasing and efficient design for more developed areas with high expectations. This design is predicted to be implemented in south-faced areas such as Karsiyaka Izmir.

Accurate position control is substantial for sun tracking mechanisms. Two main control models are studied in this thesis; position control with LDR and chronological control. Position control with LDR is a common control technique but its efficiency and reliability are questionable in cloudy days due to low radiation difference between sensors. For this reason, a control model for chronological tracking is proposed.

Solar radiation estimation is crucial to predict the solar energy production capacity for certain areas. This study showed that the present mathematical models are not accurate enough for Dokuz Eylul University Tinaztepe campus area by comparing the mathematical model results to recorded solar radiation data. Then four mathematical models have been developed with empirical methods in MatLab for each season. The developed models were compared with the recorded data, data from PVGIS for the specific area and present mathematical models. The RMSE analysis of the newly developed and present mathematical models clearly shows Unver & Goren’s models are more precise than the present model. And the comparison of the models with a different solar radiation data set from PVGIS is a corroborative evidence that new seasonal models are better fit for the research area.

PID controllers are a common form of control in industrial systems. It is preferred because of its simple structure, the small number of variables to be set, and the easy physical validation. Section 4.2 presents a proposed PID controller for position control of a chosen DC motor. Step responses of the system with P; PI and PID control are shown in figures to demonstrate the effect of PID parameters that are calculated with different tuning methods. The effect of K_p parameter in P control; K_i parameter in PI control; K_d parameter in PID control are demonstrated separately. It can easily be observed that the system response under the influence of PID controller combines the positive effects of PI and PD controllers together. PID controller was chosen for the experimental setup for the desired system behavior.

An experimental setup, a two-axis sun tracker was designed and produced to observe position control with PID control and LDR. The setup was useful to emphasize the importance of PID control in position control. The difference in behavior of the DC motor with/without the PID controller was undeniable even visibly.

Eventually, this research and the resultant thesis would be effectively useful for further solar energy and sun tracker system projects, especially for the research area, and possibly elsewhere with similar climatic conditions.

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APPENDICES

Appendix 1

	Solar Radiation [W/m^2]											
Days	**APRIL 2018**	**MAY 2018**	**JUNE 2018**	**JULY 2018**	**AUGUST 2018**	**SEPTEMBER 2018**	**OCTOBER 2018**	**NOVEMBER 2018**	**DECEMBER 2018**	**JANUARY 2019**	**FEBRUARY 2019**	**MARCH 2019**
1	455.02951	0	547.24557	633.13495	597.22666	531.31562	254.23728	344.63979	284.6746	50.45930	358.01179	404.09637
2	547.96122	380.23335	597.5733	642.14862	598.99716	530.19596	442.87472	367.32405	208.92095	108.11761	339.74041	475.03192
3	581.89934	568.56829	635.83992	641.71734	588.35145	541.44232	480.6435	352.04169	233.51945	62.17186	309.8411	468.91646
4	573.21576	516.76894	615.46761	638.82779	410.84727	556.6448	445.10393	363.05428	197.55765	170.92155	327.49262	411.54755
5	554.23132	458.96253	616.62986	619.74382	584.24298	550.79769	425.28416	346.65361	153.73336	197.85085	352.86803	453.69332
6	343.36216	233.44019	548.04416	624.76819	589.36195	538.15798	473.31619	348.28629	207.11208	196.59557	356.48054	483.91936
7	355.08989	504.5023	612.71402	632.85462	588.484	540.82028	461.78424	327.27698	291.27727	284.77845	350.21726	461.78663
8	351.74717	537.86297	602.6609	633.49349	599.22739	546.73130	430.49984	243.72117	282.02142	289.45264	197.55528	489.70029
9	554.30596	537.86945	610.46773	618.42806	593.35896	523.36628	418.55349	306.66815	63.66299	228.06961	324.26951	461.78663
10	557.3166	591.98326	634.26102	637.17761	592.94309	447.79148	402.49315	314.27408	128.49925	53.83007	371.48278	489.70029
11	248.88781	419.17772	472.70022	600.92849	600.3826	544.42271	413.51881	312.47535	236.39607	94.65928	356.91611	500.37408
12	561.0488	432.27489	650.00625	615.1485	613.34399	533.76765	411.94372	316.29372	232.85594	10.78190	157.69304	81.22992
13	544.31118	658.35439	631.38828	639.19511	587.25948	407.01686	265.32108	329.13733	89.27416	261.45287	37.050541	296.50235
14	554.05151	634.83849	577.71596	575.84137	605.69990	531.05315	401.78998	332.04056	108.05126	134.22641	392.51144	286.81698
15	503.56779	623.01244	592.48717	616.93687	580.52905	513.90358	389.61112	290.38559	183.92793	44.16040	329.36755	183.91633
16	338.34834	552.32855	417.14301	588.60422	567.02619	520.97295	378.69795	282.93819	75.41657	325.67984	381.7676	508.23693
17	565.01244	548.01579	375.01935	626.41373	559.85132	513.59915	354.22147	65.68667	98.97787	313.46228	395.55863	517.92744
18	531.61702	368.49142	525.6178	612.20014	567.58336	541.58602	330.42614	61.75664	39.75899	244.12334	396.29376	530.65449
19	387.02242	500.30303	351.14504	617.11231	557.68797	532.02225	330.84630	89.10828	210.46276	178.73767	388.29555	440.0828
20	466.52099	576.6616	351.20973	566.34599	560.37147	530.68089	345.85471	153.67447	268.53409	160.37003	393.38265	362.76361
21	558.11925	596.49952	440.95428	604.04245	556.84938	519.16846	376.26883	150.41585	263.17797	114.74049	370.35839	395.54923
22	612.00481	607.09553	370.96218	607.76476	556.20246	496.56607	361.30159	169.13572	257.20646	254.72642	425.69896	519.56453
23	579.85078	627.55141	638.91405	603.32559	531.04469	509.10828	140.02752	311.4892	190.29231	80.44378	63.30732	523.86849
24	583.25786	541.60974	597.46841	524.02282	551.98554	498.81047	303.87325	302.14129	265.83198	79.44106	188.7485	549.24337
25	579.54104	342.52993	624.55255	610.75395	556.94522	501.92622	337.89048	206.94786	32.379759	130.47762	202.44102	541.71804
26	586.38657	468.03128	456.0314	540.12876	556.56186	501.16048	396.03185	128.68617	266.80104	124.78635	394.87081	408.55933
27	557.02843	301.37431	433.64816	449.58307	550.82914	373.64687	400.93637	93.51145	126.72709	201.90193	269.14506	498.87436
28	578.10607	624.80949	490.64131	605.62325	349.11397	208.51761	383.72544	156.3784	282.02055	320.80634	310.37819	195.03169
29	547.00714	592.63921	488.804	604.37677	513.21047	404.77961	384.53784	45.65852	167.70007	172.8681	0	459.43594
30	548.37154	445.12084	420.36486	594.29853	557.54240	204.91007	328.24126	107.55364	270.21109	93.34048	0	541.80968
31	0	576.25803	0	519.84665	549.51090	0	285.30421	0	257.77829	50.39769	0	526.43595
AVERAGE	**510.14069**	**512.23896**	**530.9226**	**601.44477**	**560.40556**	**489.82943**	**372.74711**	**240.64517**	**192.73424**	**162.38167**	**312.20516**	**434.47659**

Appendix 2

East (Lux)	West (Lux)	North (Lux)	South (Lux)	Tilt Angle (Degree)	Azimuth Angle (Degree)
846.78	418.31	1167.55	251.99	26	28
854.93	435.74	1167.55	290.23	28	43
846.78	447.54	1157.85	310.18	30	45
822.58	459.48	1148.19	357.11	32	67
767.56	465.51	1110.04	406.86	34	73
628.09	471.57	1072.62	465.51	38	86
560.27	441.62	1054.19	465.51	40	86
502.43	418.31	1017.87	471.57	42	96
447.54	378.87	973.47	465.51	44	101
401.19	341.15	904.7	453.49	47	104
373.37	330.69	838.67	453.49	49	107
341.15	310.18	744.59	447.54	50	109
305.14	290.23	642.11	441.62	54	111
290.23	275.63	580.22	453.49	56	112
275.63	266.07	515.02	459.48	58	112
266.07	261.34	453.49	465.51	61	112
251.99	256.65	406.86	477.67	62	112
242.77	247.37	378.87	489.98	64	111
233.7	247.37	351.75	496.18	66	111
229.21	242.77	341.15	502.43	66	111
233.7	247.37	335.9	515.02	66	111
233.7	251.99	341.15	515.02	66	111
242.77	256.65	346.44	515.02	66	111
247.37	261.34	362.49	508.71	66	111
251.99	266.07	373.37	508.71	66	111
256.65	275.63	395.56	502.43	64	111
261.34	280.46	412.57	489.98	64	111
266.07	285.33	435.74	489.98	62	111
270.84	285.33	465.51	483.81	61	111
270.84	290.23	502.43	471.57	58	111
270.84	295.17	515.02	453.49	57	112
270.84	295.17	534.19	429.89	57	112
266.07	295.17	534.19	424.08	57	111
266.07	295.17	527.77	424.08	57	111
266.07	295.17	534.19	418.31	57	111
266.07	295.17	521.38	424.08	57	111
261.34	290.23	508.71	429.89	58	111
261.34	290.23	483.81	441.62	59	111
251.99	290.23	447.54	453.49	61	111
242.77	285.33	424.08	465.51	62	111
242.77	285.33	418.31	465.51	62	112
242.77	290.23	418.31	465.51	62	111
242.77	290.23	412.57	471.57	62	111
242.77	290.23	418.31	471.57	62	111
247.37	290.23	418.31	471.57	62	111
247.37	290.23	418.31	477.67	62	111
242.77	295.17	412.57	477.67	62	111
242.77	300.14	412.57	483.81	62	111
247.37	290.23	418.31	483.81	62	111
242.77	295.17	412.57	483.81	62	111
251.99	300.14	412.57	496.18	62	111
256.65	305.14	424.08	515.02	62	111

Appendix 2 continues

256.65	305.14	429.89	521.38	61	111
261.34	310.18	435.74	527.77	61	112
261.34	310.18	429.89	521.38	62	112
256.65	310.18	424.08	521.38	62	112
256.65	315.26	424.08	521.38	62	112
256.65	325.51	418.31	527.77	62	112
261.34	315.26	418.31	527.77	62	112
256.65	310.18	424.08	534.19	62	112
256.65	310.18	424.08	534.19	61	112
261.34	315.26	424.08	534.19	62	111
261.34	310.18	429.89	534.19	61	112
270.84	315.26	447.54	534.19	60	112
270.84	315.26	465.51	527.77	59	111
275.63	320.37	489.98	515.02	58	111
280.46	325.51	515.02	502.43	57	111
280.46	325.51	534.19	496.18	57	111
275.63	325.51	527.77	489.98	56	111
275.63	315.26	527.77	483.81	56	112
275.63	320.37	527.77	477.67	57	112
280.46	315.26	527.77	477.67	57	111
275.63	315.26	527.77	477.67	57	111
275.63	310.18	527.77	477.67	57	111
275.63	310.18	527.77	489.98	57	111
280.46	310.18	521.38	502.43	59	111
280.46	305.14	515.02	508.71	58	111
280.46	305.14	515.02	515.02	58	111
280.46	305.14	515.02	521.38	58	111
280.46	305.14	508.71	521.38	58	111
275.63	305.14	508.71	521.38	57	112
280.46	305.14	508.71	521.38	58	112
280.46	305.14	502.43	521.38	58	111
280.46	300.14	502.43	515.02	58	112
275.63	300.14	502.43	515.02	58	112
280.46	300.14	502.43	521.38	58	112
275.63	300.14	496.18	515.02	58	112
275.63	295.17	502.43	521.38	58	112
280.46	300.14	502.43	521.38	58	111
280.46	295.17	508.71	521.38	57	111
280.46	295.17	502.43	527.77	58	111
280.46	295.17	508.71	527.77	58	111
280.46	295.17	515.02	527.77	58	111
280.46	295.17	515.02	534.19	58	111
280.46	295.17	515.02	534.19	57	111
285.33	295.17	527.77	540.66	58	111
285.33	300.14	521.38	547.16	57	111
280.46	305.14	515.02	540.66	58	111
280.46	305.14	508.71	540.66	58	110
280.46	305.14	508.71	540.66	58	111
280.46	305.14	502.43	540.66	58	111
280.46	310.18	508.71	547.16	58	110
280.46	305.14	502.43	547.16	58	110
285.33	310.18	502.43	547.16	58	111
285.33	310.18	502.43	547.16	58	110
275.63	310.18	496.18	540.66	58	110
280.46	310.18	496.18	540.66	57	110

Appendix 2 continues

280.46	310.18	489.98	540.66	58	109
275.63	310.18	483.81	534.19	57	109
275.63	310.18	483.81	534.19	58	110
275.63	310.18	489.98	534.19	57	110
275.63	310.18	477.67	527.77	58	109
275.63	305.14	477.67	534.19	58	110
275.63	305.14	483.81	534.19	58	109
275.63	310.18	489.98	534.19	58	110
275.63	310.18	489.98	534.19	57	109
275.63	305.14	477.67	534.19	58	108
275.63	310.18	483.81	527.77	58	108
270.84	310.18	477.67	521.38	58	111
266.07	310.18	465.51	515.02	58	116
256.65	315.26	453.49	515.02	58	116
256.65	315.26	453.49	508.71	58	117
251.99	315.26	441.62	502.43	58	117
251.99	315.26	441.62	508.71	57	117
251.99	320.37	435.74	508.71	57	116
251.99	315.26	435.74	508.71	58	116
256.65	315.26	441.62	515.02	58	116
261.34	315.26	429.89	521.38	58	116
261.34	315.26	447.54	534.19	58	116
270.84	315.26	453.49	540.66	57	116
275.63	315.26	471.57	560.27	57	116
280.46	315.26	489.98	560.27	57	116
290.23	320.37	521.38	566.88	56	116
290.23	320.37	553.7	560.27	55	116
300.14	320.37	580.22	553.7	54	116
305.14	325.51	593.71	553.7	54	116
305.14	325.51	593.71	553.7	54	116
305.14	325.51	607.35	553.7	54	116
305.14	325.51	614.22	553.7	54	116
305.14	330.69	607.35	553.7	54	116
305.14	325.51	607.35	547.16	54	116
305.14	330.69	607.35	560.27	54	116
305.14	325.51	593.71	560.27	56	116
300.14	325.51	586.95	560.27	56	116
300.14	320.37	580.22	566.88	57	116
295.17	320.37	566.88	566.88	57	116
295.17	315.26	566.88	560.27	57	116
290.23	310.18	560.27	553.7	57	116
285.33	310.18	553.7	547.16	57	116
290.23	310.18	553.7	547.16	57	116
290.23	305.14	553.7	540.66	57	115
285.33	310.18	547.16	540.66	57	115
290.23	310.18	553.7	540.66	57	115
290.23	310.18	547.16	547.16	57	117
285.33	305.14	547.16	540.66	57	118
290.23	310.18	540.66	540.66	57	118
275.63	305.14	534.19	540.66	57	118
280.46	310.18	540.66	547.16	57	118
285.33	305.14	540.66	547.16	57	118
290.23	305.14	540.66	540.66	57	118
285.33	305.14	540.66	547.16	57	118
290.23	305.14	540.66	547.16	58	118

Appendix 2 continues

285.33	305.14	540.66	547.16	57	118
290.23	300.14	547.16	547.16	57	118
290.23	305.14	553.7	547.16	57	118
290.23	305.14	547.16	553.7	57	118
290.23	305.14	547.16	553.7	57	118
290.23	310.18	547.16	553.7	57	118
290.23	305.14	547.16	553.7	57	118
290.23	305.14	540.66	553.7	57	118
290.23	295.17	540.66	553.7	57	118
290.23	300.14	540.66	553.7	57	118
285.33	300.14	540.66	553.7	57	118
290.23	300.14	540.66	553.7	57	118
290.23	305.14	540.66	553.7	57	118
290.23	295.17	540.66	553.7	57	118
295.17	300.14	547.16	560.27	57	118
300.14	305.14	553.7	566.88	57	118
295.17	300.14	553.7	566.88	57	118
300.14	305.14	553.7	566.88	57	118
300.14	300.14	553.7	573.53	57	118
295.17	300.14	547.16	560.27	57	118
290.23	300.14	547.16	566.88	57	118
285.33	300.14	534.19	560.27	57	118
285.33	300.14	534.19	553.7	57	118
285.33	300.14	527.77	553.7	57	118
285.33	300.14	527.77	547.16	57	118
285.33	300.14	521.38	547.16	57	118
285.33	305.14	534.19	547.16	57	118
285.33	305.14	527.77	553.7	57	118
285.33	305.14	534.19	547.16	57	118
285.33	305.14	540.66	553.7	57	118
290.23	310.18	540.66	560.27	56	118
290.23	310.18	547.16	553.7	57	118
295.17	310.18	547.16	560.27	57	118
295.17	315.26	553.7	560.27	57	118
290.23	315.26	560.27	560.27	57	118
295.17	315.26	553.7	560.27	57	118
290.23	320.37	553.7	566.88	57	118
290.23	320.37	553.7	566.88	57	118
290.23	325.51	553.7	566.88	57	118
290.23	325.51	553.7	573.53	57	118
300.14	330.69	560.27	580.22	57	118
295.17	330.69	560.27	580.22	57	118
300.14	335.9	566.88	580.22	57	118
300.14	330.69	566.88	580.22	57	118
300.14	330.69	566.88	580.22	57	118
300.14	330.69	566.88	580.22	57	118
295.17	330.69	566.88	580.22	57	118
300.14	330.69	566.88	580.22	57	118
295.17	330.69	560.27	586.95	57	118
305.14	330.69	560.27	593.71	58	118
300.14	335.9	566.88	600.51	57	118
305.14	341.15	566.88	607.35	57	117
305.14	335.9	566.88	607.35	57	118
305.14	335.9	566.88	607.35	57	118
305.14	341.15	566.88	607.35	57	118

Appendix 2 continues

305.14	335.9	560.27	607.35	57	118
300.14	341.15	560.27	614.22	57	118
305.14	330.69	566.88	614.22	57	118
305.14	335.9	566.88	614.22	57	118
310.18	341.15	566.88	614.22	57	118
310.18	335.9	573.53	621.14	57	118
310.18	341.15	580.22	621.14	57	118
310.18	341.15	580.22	621.14	57	118
310.18	346.44	573.53	621.14	57	118
310.18	346.44	580.22	621.14	57	118
310.18	341.15	586.95	621.14	57	118
315.26	341.15	593.71	621.14	57	118
320.37	346.44	600.51	621.14	57	118
320.37	346.44	600.51	621.14	57	118
320.37	346.44	600.51	635.08	57	118
325.51	351.75	607.35	635.08	57	118
330.69	346.44	614.22	635.08	57	118
330.69	351.75	621.14	642.11	57	118
330.69	351.75	621.14	642.11	57	118
335.9	357.11	621.14	649.17	57	118
341.15	362.49	635.08	649.17	57	118
346.44	362.49	649.17	656.28	57	118
351.75	362.49	656.28	656.28	57	118
351.75	362.49	663.42	663.42	57	118
351.75	367.92	663.42	656.28	57	118
351.75	367.92	663.42	663.42	57	118
351.75	362.49	656.28	656.28	57	118