Research Article / Araştırma Makalesi GU J Sci, Part A, 9(2): 62-78 (2022) https://doi.org/10.54287/gujsa.1085005

Gazi University
Journal of Science
PART A: ENGINEERING AND INNOVATION
http://dergipark.org.tr/gujsa

An Approach on Developing a Dynamic Wind-Solar Map for Tracking Electricity Production Potential and Energy Harvest

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Keywords

Renewable Energy
Photovoltaic
Wind
Dynamic Map
Optimization

Abstract

Increasing energy demand brings in technical, environmental and economic problems as the production processes evolve. In this parallel, many countries are trying to satisfy the increasing energy demand using renewable energy sources. The scope of this study is to develope a mathematical model and data monitoring-evaluation software for wind and solar renewable energy sources, which can dynamically evaluate meteorological data measurements and make more precise energy harvest estimation with the data obtained. It is aimed to create a web based "Dynamic Wind-Sun Map of Turkey". Through the developed software; instant data can be analyzed and instantaneous electrical energy values produced from wind and solar energy sources can be calculated. Thus, it can help create a system that allows regional management in energy production and is compatible. Within the scope of the study, a mathematical model expressing the problem was created by using some mathematical optimization methods. The created model was converted into a web-based software. PHP software development platform and MySQL database language were used during the software creation. The software developed within the scope of the study has analogues in the world literature. However, no study has been found in this context in Turkey. Especially since it can use real-time data and includes wind-photovoltaic calculations together, this software distinguishes it from its peers.

Cite

Salmanoğlu, F., & Çetin, N. S., (2022). An Approach on Developing a Dynamic Wind-Solar Map for Tracking Electricity Production Potential and Energy Harvest. *GU J Sci, Part A*, *9*(2), 62-78.

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Article Process

Submission Date	09.03.2022
Revision Date	02.06.2022
Accepted Date	06.06.2022
Published Date	07.06.2022

1. INTRODUCTION

With the technological change, the increase in energy demand shows itself day by day and this change naturally brings in technical, environmental and economic problems. According to International Energy Agency (IEA) data, global electrical energy demand decreased by about 1% in 2020 due to the effects of the Covid-19 pandemic. However, with the effect of the global economic recovery, the world electricity demand is expected to increase by 5% until the end of 2021 and by 4% in 2022. It is thought that almost half of this increase will come from fossil fuels, especially coal. This increase indicates that CO_2 emissions from the energy sector will reach record levels in 2022. 85% of this energy need in the world is expected to be met from fossil resources, also called limited resources (coal, oil, natural gas, etc.) (IEA, 2021).

Although the annual average growth in global energy consumption has slowed since 2020, it is predicted that the average annual growth in global energy consumption from 2010 to 2030 will be 1.7% (BP, 2011).

The Kyoto Protocol, which currently has 192 parties, was accepted on 11 December 1997, but entered into force on 16 February 2005 due to a complex ratification process. The Kyoto Protocol sets binding emission reduction targets for 37 industrialized countries and the European Union. Overall, the Protocol aims to contribute to an average of 5% emissions reductions compared to 1990 levels over the five-year period

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covering the first commitment period 2008-2012 (UNFCCC, 2021). Although this target has not been achieved yet, alternative ways of energy production are gaining more and more important in order to respond to the increasing energy demand on the one hand and to reduce greenhouse gas emissions on the other. Renewable energy sources lead the way in these alternatives, and the most used energy sources in the world after fossil fuels are the Sun and Wind.

Within the scope of this study, a dynamic data source has been created to ensure reliable calculations and supply continuity, especially for wind and solar energy. The mathematical model and data monitoring and evaluation software developed here can dynamically process meteorological data measurements. The software analyzes instant data and optimizes the electrical energy values that can be produced instantly from wind and solar energy sources.

The increasing use of fossil fuels worldwide, especially after the industrial revolution, has caused many negative environmental effects and problems. Accordingly, research and development studies on the use of renewable energy sources have accelerated. One of the notable indicators of this is the recent increase in the funds allocated by developed countries for R&D studies for the use and expansion of clean energy resources.

Renewable energy sources do not emit greenhouse gases, which affect global climate conditions, within their energy conversion processes. Moreover, these resources are generally endless, inexhaustible and free, do not produce noise, allow electricity use in areas far from electricity networks and do not require much maintenance. The payback period for the initial investment costs is short and it is getting even shorter with the technological developments which both decreasing the initial costs and increasing the process efficiencies. Systems based on the Sun and wind, which are the most widely used renewable energy sources in the world today, also have an important role in creating regional employment.

As a result of the combustion of fossile fuels such as coal, petroleum derivatives and natural gas, various amounts of carbon dioxide (CO_2) are emitted into the atmosphere depending on the amount of energy produced.

According to the International Energy Agency (IEA) data, although global CO_2 emissions decreased in 2020 due to the pandemic, they increased by about 5% in 2021, reaching the level of 3.3×10^{10} tons and approaching the 2018-2019 peak (IEA, 2020). Half of these greenhouse gas is released into the atmosphere, while the other half dissolves in the oceans and seas. This process introduces the concept of "Global warming" in parallel with the increase in the amount of greenhouse gases in the atmosphere. Accordingly, producing a decelerating solution to the global warming problem will only be possible using renewable energy sources.

Renewable energy sources are growing rapidly in the global market and are at the focus of attention for researchers and the industry. It is vital for investment and investor to determine the field to be invested in, and examine the field's characteristics in a multi-faceted manner, especially for wind and solar energy investments, since they are time dependent and intermittent. The largest obstacle in front of investments in renewable energy sources is the high initial investment costs. In this case, the first question that comes to the mind of the investor is how many years the system will pay itself back. For this reason, potential determination in the region where the implementation will be made is very important in terms of the payback period of the system. As a result of the literature review conducted within the scope of this study, it is seen that the studies on data monitoring and evaluation started in the 90s. However, it was seen that the studies on monitoring and potential determination in renewable energy systems intensified at the end of the 90s (NREL, 2021). In this study, a software has been developed that dynamically evaluates high-resolution data coming from data measurement stations located at specific measurement points and presents the outputs obtained as a dynamic evaluation map, unlike the theoretical studies we usually encounter.

In Turkey, there are static wind and solar energy maps, which are studied by the Renewable Energy Resources Branch Directorate of the Ministry of Energy and Natural Resources, and there is no study that includes dynamic and comprehensive calculations (EİGM, 2022a, 2022b).

When we take a look at the international literature, dynamic data for Wind, Solar, Biomass, Hydrogen and Geothermal energy sources developed by the Geographic Information System (GIS) team of “National Renewable Energy Laboratory – NREL”, one of the world's largest renewable energy laboratories in the United States. maps were created and these studies were seen to be a structure that has been started since 1986. NREL's Geographic Information Systems team presents high-resolution wind and solar data and analyzes for the evaluation of wind and solar resources in the United States, with the dynamic map developed similar to the software we developed in this study. The national wind and solar resource assessment studies initiated by NREL for the US Department of Energy in 1986 were published as the US Wind and Solar Energy Atlas in October of the same year (NREL, 2021).

The resulting software package aims to create a resource that can be a reference for scientific research and researchers, as well as institutions and organizations working in this field. The lack of a reliable database and source in this sector and the static nature of the available maps for Turkey, would underline the value of successful development of such dynamic wind-solar maps to be presented to the sector. The software developed within the scope of the study has analogues in the world literature. However, no study has been found in this context in Turkey. Especially since it can use real-time data and includes wind-photovoltaic calculations together, this software distinguishes it from its peers.

2. MATERIAL AND METHOD

Within the scope of the study, the following calculation methods were used.

2.1. Calculations for Photovoltaics

Sun Angles

Some of the sun angles taken into account in the calculations are given in (Honsberg & Bowden, 2019). (Figure 1)

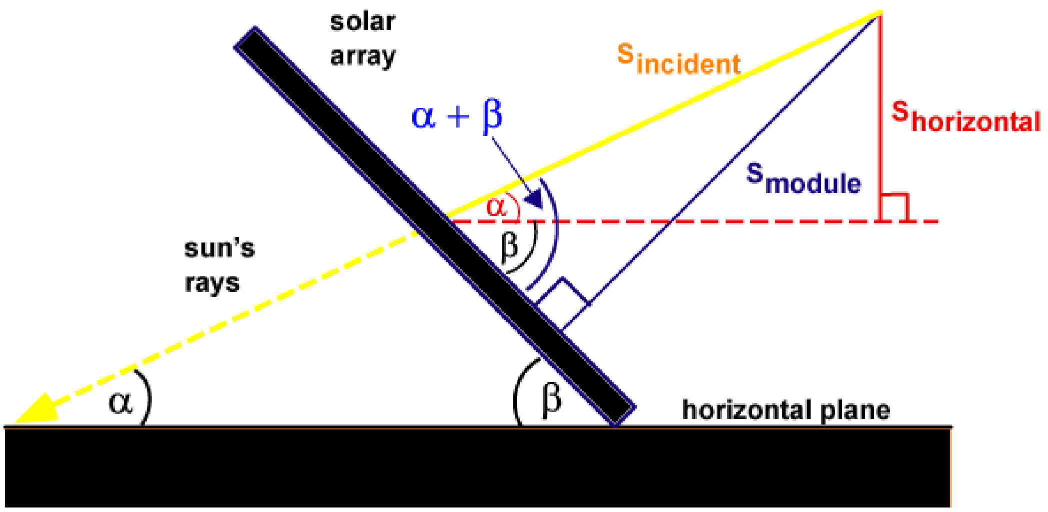


Figure 1. Sun angles (Honsberg & Bowden, 2019)

Declination Angle, δ: It is the angle that the sun's rays make with the earth's equatorial plane. It can also be defined as the angle between the direction connecting the centers of Sun and Earth and its projection on the equatorial plane (Stanciu & Stanciu, 2014). (Figure 2)

The declination angle takes the extreme values of -23.45° at the winter solstice on December 21st and +23.45° at the summer solstice of June 21st. On March 21st at the spring equinox and September 21st at the autumn equinox, the declination angle becomes zero (Stanciu & Stanciu, 2014). (Figure 3)

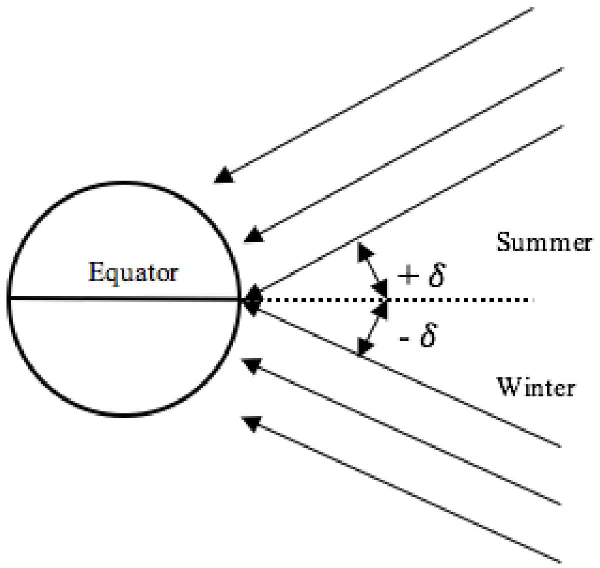


Figure 2. Declination angle

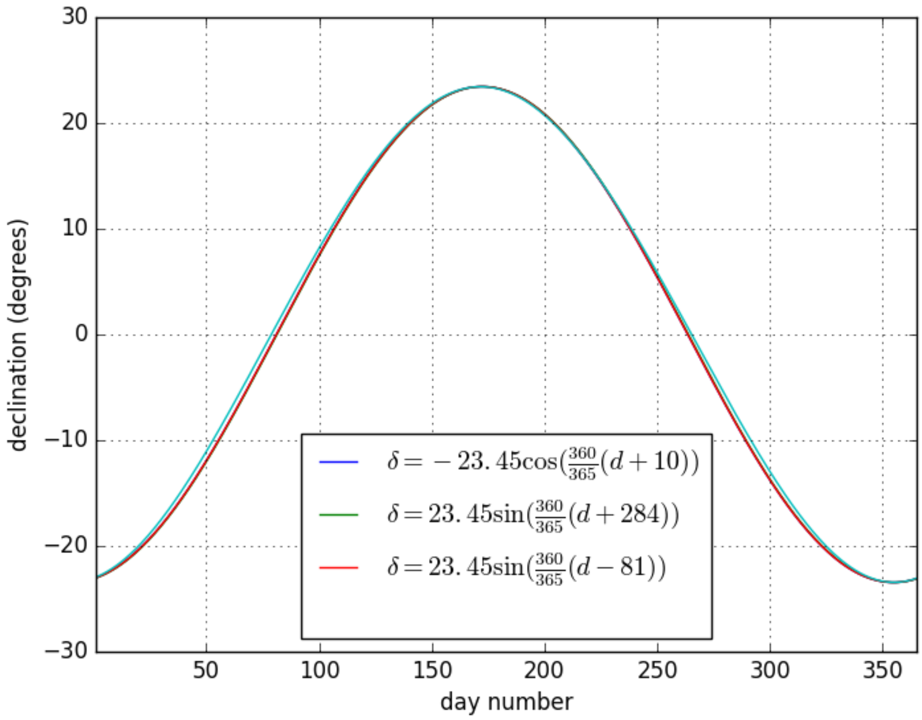


Figure 3. Variation of declination angle according to months

Declination Angle, with n number of days starting from January 1st, which is the first day of the year, with Equation 1;

$$\delta = 23{,}45 \; x \; sin \; (360 \; x \; (284 + n)/365) \tag{1}$$

is calculated as (Stanciu & Stanciu, 2014).

Optimum Tilt Angle, β_{opt}: It is the angle that the PV panel must make with the horizontal plane in order for the sun rays to fall vertically on the PV panel. It is calculated with Equation 2 (Sharma et al., 2021).

$$\beta_{opt} = \phi - \delta \qquad (2)$$

Calculation of Incoming Radiation Value to a Sloped and South Deflected Surface

In order to achieve maximum energy conversion in PV systems, the sun's rays must come to the PV panel at a right angle and the PV panels must be placed facing south. However, in some cases, it may not be possible to capture this environment. Therefore, if the standing angle (β) of the PV panel on the plane and the angle of deviation from the south (σ) are known, the solar radiation value (S_{module}) on the PV panel at that moment can be calculated by the model expressed in Equation 3 (Honsberg & Bowden, 2019; Takilalte et al., 2020; Amiri et al., 2021).

$$S_{module} = S_{incident}.(Cos\alpha \,.Sin\,\beta \,.Cos\boldsymbol{\sigma} \,+ Sin\alpha \,.Cos\,\beta) \qquad (3)$$

$$S_{incident} = S_{horizontal}/Sin\alpha \qquad (4)$$

System Efficiency

No system works with 100% efficiency. Every component, and therefore every system containing these components, has a conversion efficiency calculated accordingly. In PV systems, the system efficiency is calculated with Equation 5 (Salmanoğlu & Çetin, 2013).

$$\eta_{sys} = \eta_{PV}\; x\; \eta_{inv}\; x\; \eta_{bat}\; x\; 0{,}9 \qquad (5)$$

η_{sys} : *system efficiency,*

η_{PV} : *PV panel efficiency,*

η_{inv} : *invertor efficiency,*

η_{bat} : *battery efficiency.*

In this model, PV panel efficiency is an effective element when calculating system efficiency η_sist. The effect of temperature on η_PV, which is expressed as PV panel efficiency, is calculated with the model expressed in Equation 6 (Sultan et al., 2020).

$$\eta_{PV} = \eta_r[1 - \beta_T(T_c - T_r)] \qquad (6)$$

η_r : *module efficiency expressed by the module manufacturer,*

β_T : *string efficiency temperature coefficient,*

T_c : *average monthly cell temperature,*

T_r : *reference temperature given for cell efficiency.*

Calculation of the Annual Expected Energy Harvest Against the Determined PV Panel Installed Power

The model in Equation 7 is used when calculating the annual electrical energy production for the electrical energy produced by the photovoltaic method from solar energy (Salmanoğlu & Çetin, 2013).

$$G_{PV} = \sum_{k=1}^{8760} \eta_{sys} \, . I_k \tag{7}$$

I_k : *total solar radiation on 1 m^2 area at the k hour of the year, kWh/m^2,*

G_{PV} : *annual energy harvest of 1 m^2 photovoltaic panel.*

The mathematical model on which the software developed within the scope of this study was built, accepts readily available data provided by meteorological measurement stations as input and transform them into an adjusted and utilizable form. These data and derived results of the calculations are then presented dynamically to the user. The outputs are also rendered and shown on a map which is a powerful and comprehensive user interface choice.

2.2. The Calculation for Wind Power System

The primary parameter in calculating the electrical power obtained from the turbine is the wind speed and it is directly related to the height at which the measurement was made. For this reason, the measured wind speed values must be converted to the height at which the turbine is installed. Based on this conversion, it is possible to calculate the energy and power of the system or the site to be installed more reliably.

In the literature, the "Hellman Equation" expressed in Equation 8 is used in order to calculate the wind speed according to altitude mathematically (Salmanoğlu & Çetin, 2013). Wind speed data are obtained from the wind measurement station at a height of 30m, located within the Ege University Solar Energy Institute. The Hellman elevation equation is used to calculate the wind speed at tower height according to the wind turbine selected from the database.

$$V_r = V_{ref} . \left(H/H_{ref}\right)^{\mu} \tag{8}$$

V_r : *wind speed (m/s) to be obtained as a result of the calculation (wind speed value increased to tower height),*

V_{ref} : *reference wind speed (m/s) used in the calculation,*

H : *hub height (m),*

H_{ref} : *reference height (m),*

μ : *friction coefficient (Table 1).*

Table 1. *Friction coefficient for a variety of landscapes (Suvire, 2011)*

Landscape type	Friction coefficient
Lakes, ocean and smooth hard ground	0.10
Grasslands (ground level)	0.15
Tall crops, hedges and shrubs	0.20
Heavily forested land	0.25
Small town with some trees and shrubs	0.30
City areas with high rise buildings	0.40

The mathematical expression that can be used to obtain the power output characteristic of the wind turbine for the wind speed values derived for the desired heights with the Hellman equation is given in Equation 9. Wind speed measurements should be taken at two different heights at each measurement tower. Thus, the actual values of the roughness coefficient in the environment will be computable (Fotso et al., 2021).

$$P_W(V_r) = \begin{pmatrix} 0\,, & V_r<V_{ci} \\ C_p.\left(\frac{1}{2}.\rho.(\pi.r^2).V^3\right), & V_{ci}<V_r<V_{rated} \\ P_{r,} & V_{rated}<V_r<V_{co} \\ 0, & V_r>V_{co} \end{pmatrix} \tag{9}$$

$P_W(V_r)$: power generation of wind turbine at V_r wind speed (W),

P_r : rated power of wind turbine (W),

V_r : wind speed at hub height (m/s),

V_{ci} : cut-inn wind speed (m/s),

V_{rated} : wind speed at the rated power of the wind turbine (m/s),

V_{co} : cut-out wind speed (m/s).

Wind speed exhibits a fluctuating structure during the day. For this reason, wind blowing times should be known in the calculation of electrical energy obtained from wind energy. When this data is not present, it is essential to drive it using a proper mathematical approach. to synthetically derive it using a proper mathematical approach. Wind blowing times for the locations where no measurements are taken can be calculated from the meteorological data obtained from surrounding locations. For this calculation, "Rayleigh Distribution Function" and "Weibull Function", which are continuous probability distributions, are frequently used in probability theory and statistical sciences. The hourly blowing times of the wind speed are calculated with the help of the "Rayleigh Distribution Function" as in Equation 10 (Serban et al., 2020).

$$h_r = 1.\frac{\pi}{2}.(V_i/V_{ave}^2).e^{-\frac{\pi}{4}(V_i/V_{ave})^2} \tag{10}$$

Here;

V_i : wind speed to be calculated (m/s),

V_{ave} : average wind speed (m/s),

h_r : daily blowing time (h).

As a result of these calculations, the hourly electrical energy value obtained from the wind turbine planned to be used in a wind power system can be calculated with the model in Equation 11.

$$G_W = \sum_{i=1}^{8760}\sum_{j=1}^{25} h_{r,i,j}.C_p.\left(\frac{1}{2}.\rho(\pi r^2).V^3\right)/1000 \tag{11}$$

Here,

$h_{r,i,j}$: wind blowing time at i m/s wind speed at j hour of the year,

C_p : wind turbine power coefficient.

2.3. Database Design

The software developed here was designed in a modular structure. The modules of the software are;

- Dynamic Data Monitoring Module,
- System Design Module
- Calculation Module,
- Carbon Footprint and Depreciation Calculation Module
- Reporting Module

System design and carbon footprint modules are hosted on the local server and the relevant data is stored in its own database. The Calculation and Reporting modules requires a valid password provided by the user. Access control is performed with a password to be determined and controlled via an application programming interface (API) running on the user side. The developer server hosts the password and license validity information in its database and answers the requests within license coverage. The general structure of the system can be seen in Figure 4.

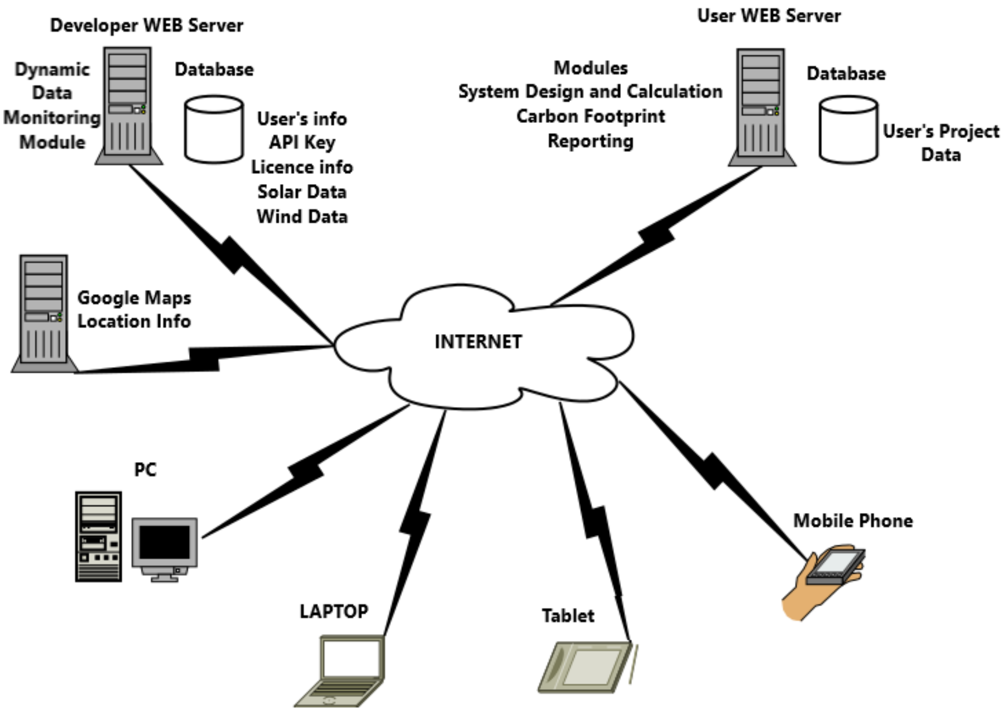


Figure 4. Working of the software over the internet

The software is developed with PHP programming language and user information is stored in MySQL database. The reasons for choosing this duo are that they provide all software needs, are open source and have low licensing costs.

Calculation and Reporting modules are hosted on the developer server and users with software licenses can benefit from these modules via WEB Service. The user requests account results, reports and analyzes from the WEB Service software on the developer servers. If the password (API password) transmitted with the request is valid, the modules fulfill the requests and send the results in JSON format to the user server. The flow diagram, which algorithmically expresses the working stages required to create a dynamic wind-solar map, is given in Figure 5.

The database developed in the MySQL environment generally contains user and project information, dynamic meteorological information and tables containing the definitions of the components used in the system and the relationship between these tables. Some examples of tables in the database are shown in Figures 6-9.

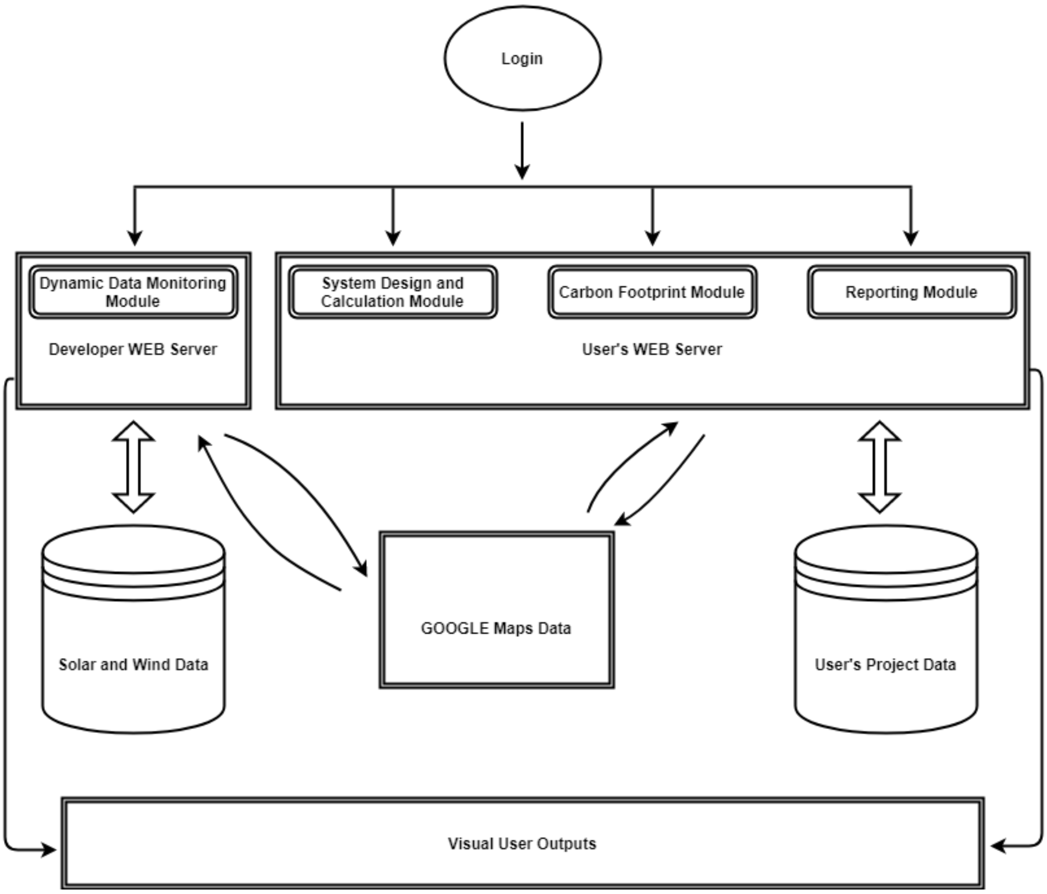
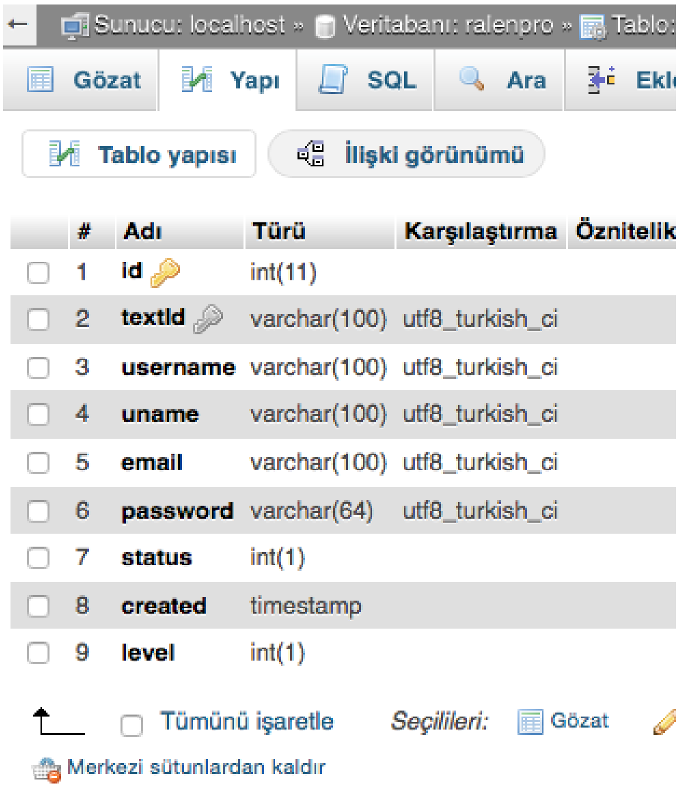


Figure 5. General working principle of the designed system



#	Adı	Türü	Karşılaştırma	Öznitelik
1	id	int(11)		
2	textId	varchar(100)	utf8_turkish_ci	
3	username	varchar(100)	utf8_turkish_ci	
4	uname	varchar(100)	utf8_turkish_ci	
5	email	varchar(100)	utf8_turkish_ci	
6	password	varchar(64)	utf8_turkish_ci	
7	status	int(1)		
8	created	timestamp		
9	level	int(1)		

Figure 6. Table containing user information in the designed database

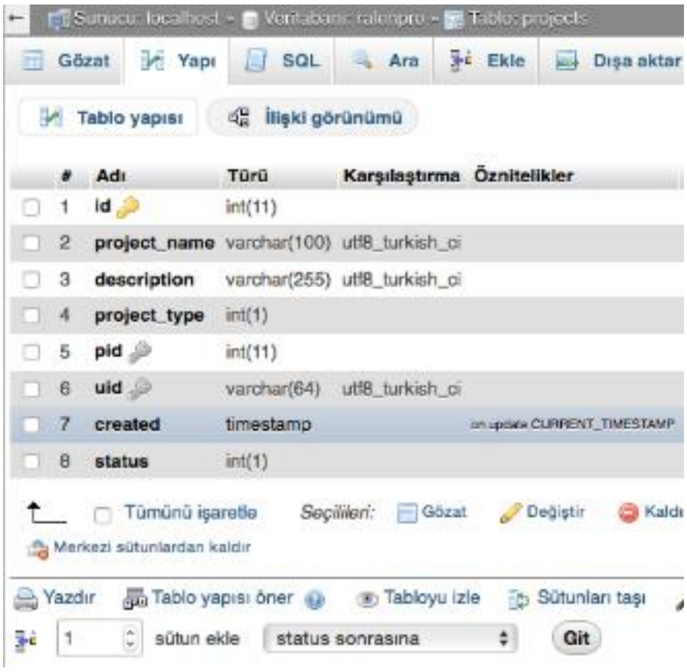


Figure 7. Table for project information in the designed database

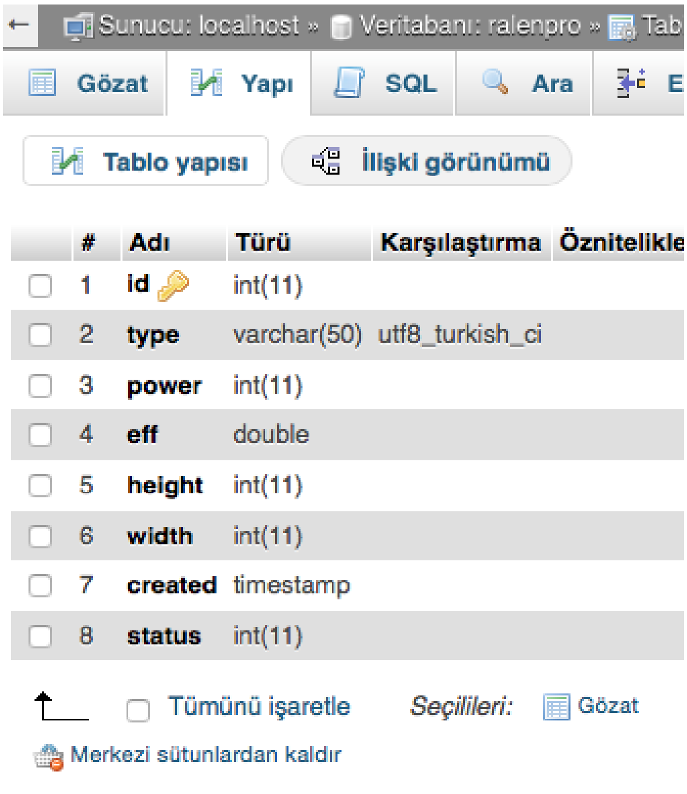


Figure 8. Table for PV panel information in the designed database

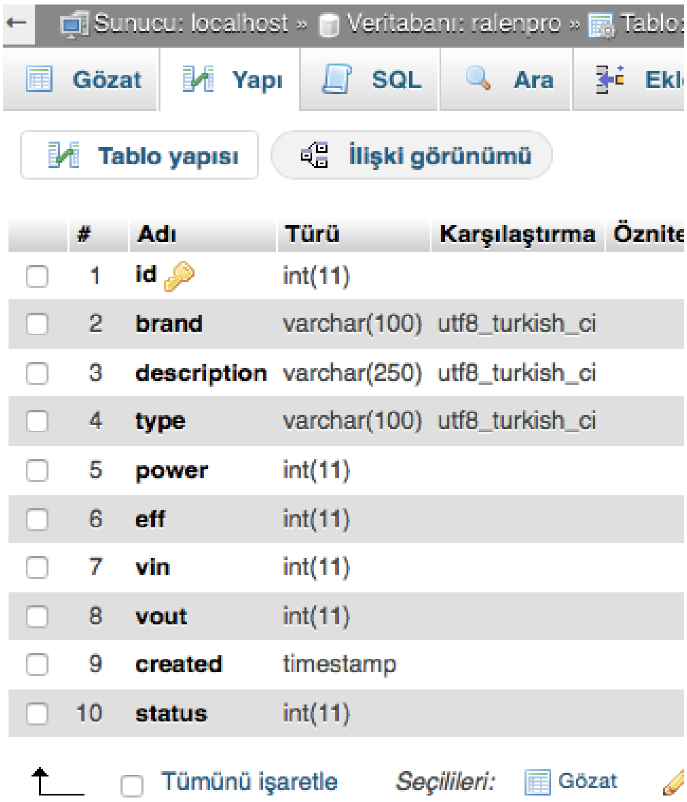


Figure 9. Table for inverter information in the designed database

3. RESULTS AND DISCUSSION

Since the number of data providing stations was limited during the tests of the study, a data generator was developed to generate random data to be used in the software. The random data produced in certain ranges and properties, were used to input dynamic evaluation and modeling software. It has been proven that the mathematical model and the developed software structure work smoothly with virtual data.

Software is able to read and process the parametric values like wind speed and direction, temperature, pressure, humidity, and solar irradiation within one-minute resolution.

The software and the mathematical model it contains can calculate and report;

- Optimum angle for PV panel placement,
- Hourly, daily, monthly, annual energy harvest according to the selected PV panel and wind turbine characteristics,
- Avoided carbon emissions,
- Southward deviation energy losses in PV systems,
- Energy losses in PV systems deviating from the optimum angle,
- Optimum system design according to the energy consumption specified by the user.

Screenshots of the developed software and the function of each software module are explained below.

Developed Software

When the user accesses the system website over the internet, the “User Login Screen” appears in Figure 10, which requests user information and queries whether the user has permission to access the system.

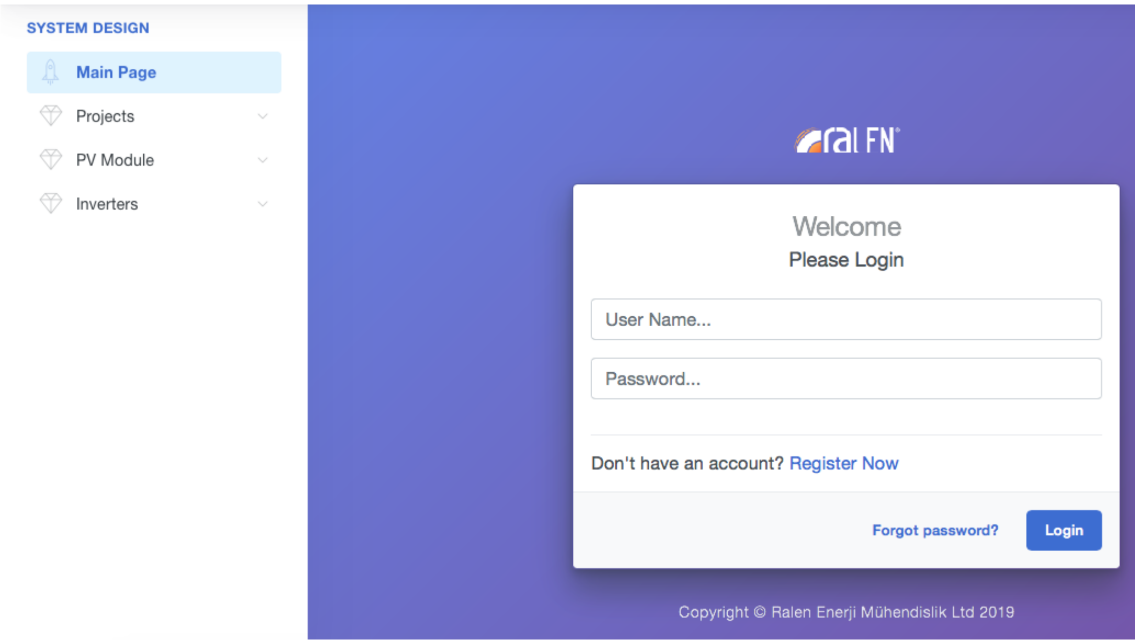


Figure 10. User login

The user can sign in to the system with the valid "User Name" and "Password" pair assigned to him/her, and if he/she does not have a User Name and Password, they can sign up to the system via this screen.

Once the user provides this information and the connection to the system is established, the "Module Selection Screen" shown in Figure 11 is shown.

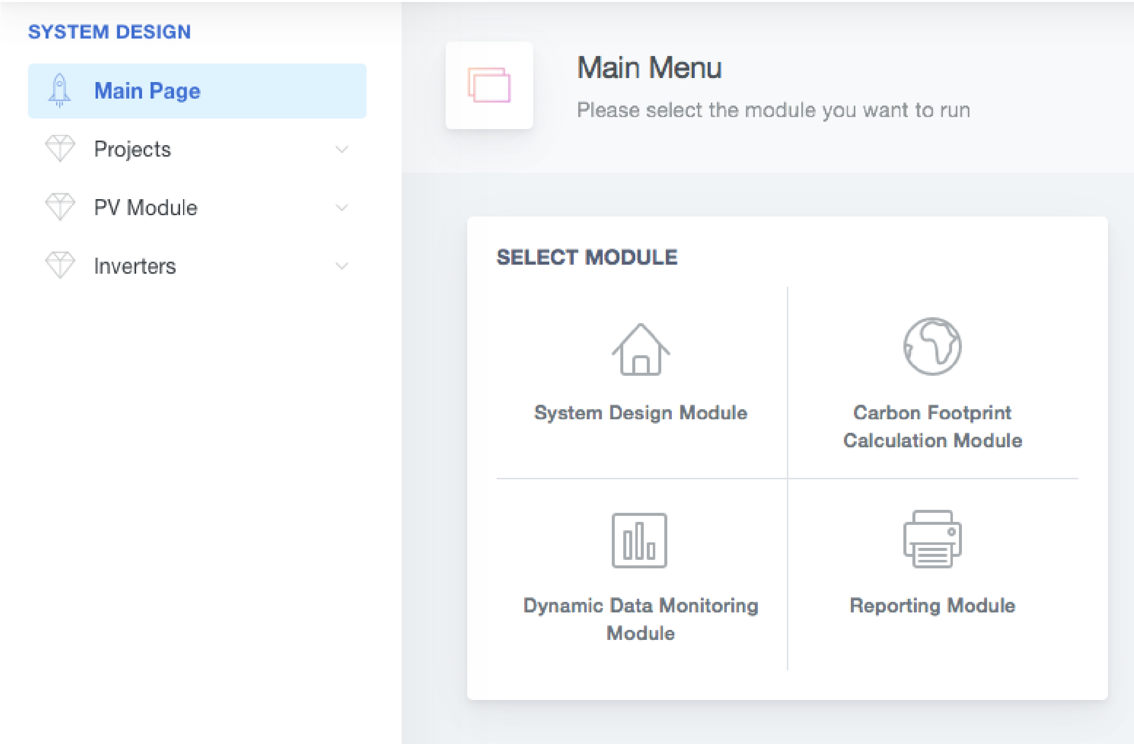


Figure 11. Module selection

The user can choose among the four main modules on this screen.

When the "System Design" module is clicked, firstly, basic information like the "Project Name" and "Project Type" of the project is requested to be entered in the screen shown in Figure 12.

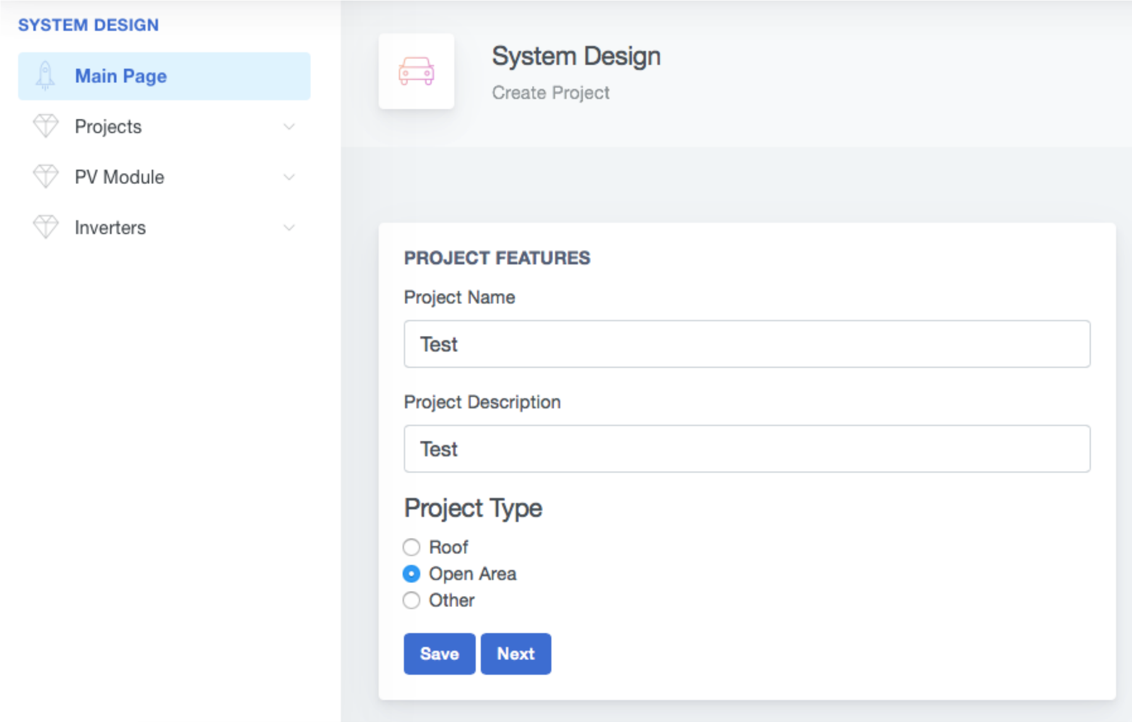


Figure 12. System design module project description screen

After entering the required data on the screen shown in Figure 12, the project information is saved with the Save button and the "Next Step" button is clicked.

Afterwards, the software directs the user to the Location Screen in order to select the location in Figure 13.

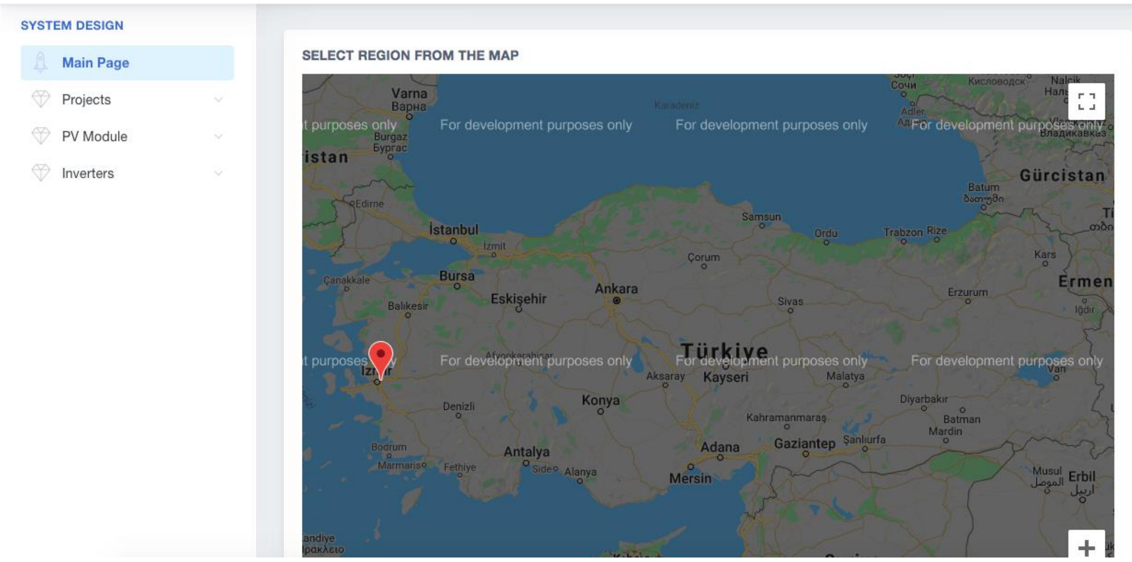


Figure 13. System design module location screen

When the location where the project design will be made is selected on the screen and the next step is taken, certain options regarding the system design are presented to the user, as seen in Figure 14.

The user must first define the physical size of the area where the system will be designed, via the screen in Figure 14. For the system area whose size is determined, there are options such as placing the maximum PV panel that will fit in the area, entering the number of panels and determining the installed power. In each of these options, the fixed angle of the PV panel and the deviation of the installation area from the south can be defined to the system by the user. After selection, design continues.

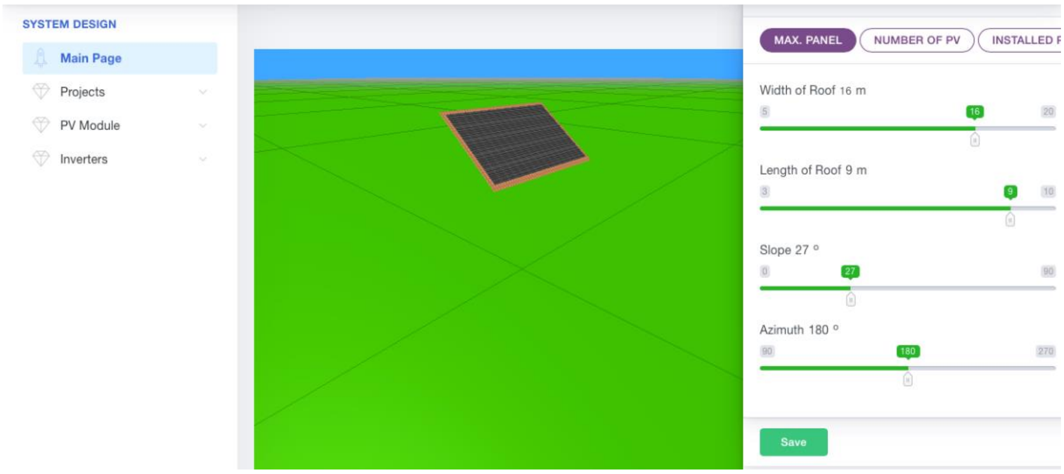


Figure 14. System design module system properties determination screen

When the "Dynamic Data Monitoring Module" is clicked by the user via the Module Selection Screen, the change of wind-sun and other meteorological data for the previously selected location is dynamically presented to the user on this screen. When the "Data Reporting" button in this module is clicked, the data is reported according to the selected date range and the data is presented to the user graphically, as shown in Figure 15.

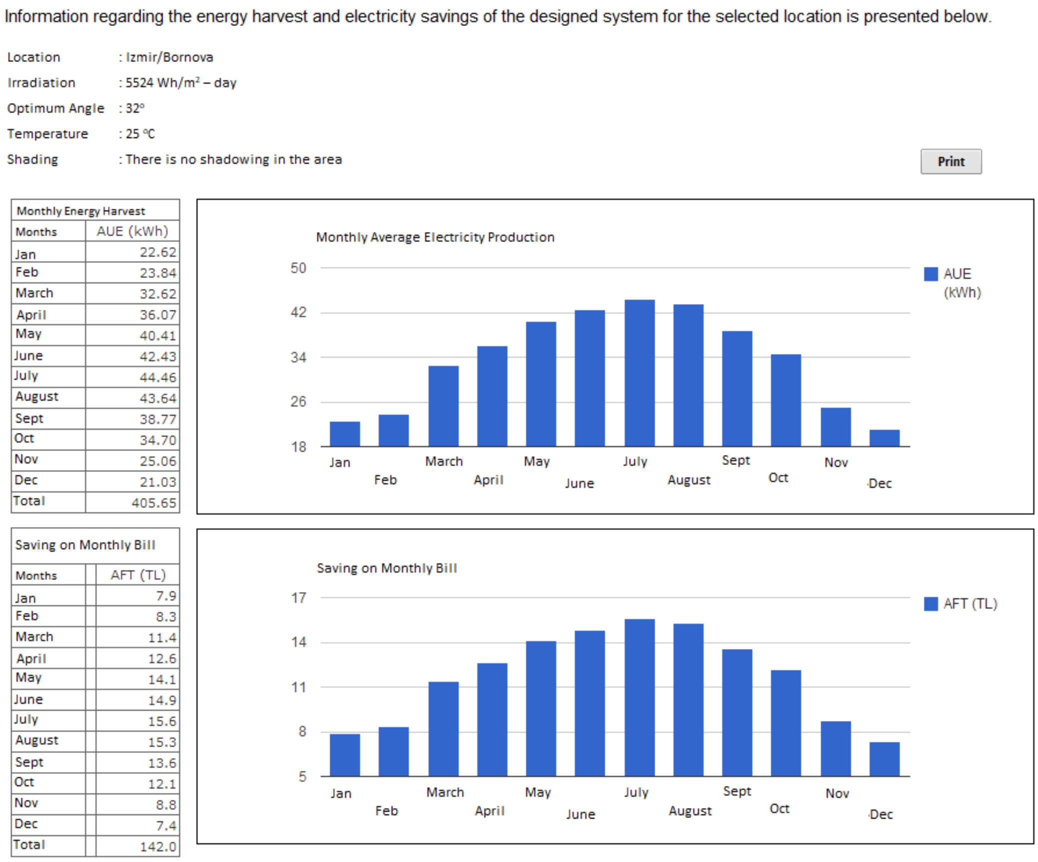


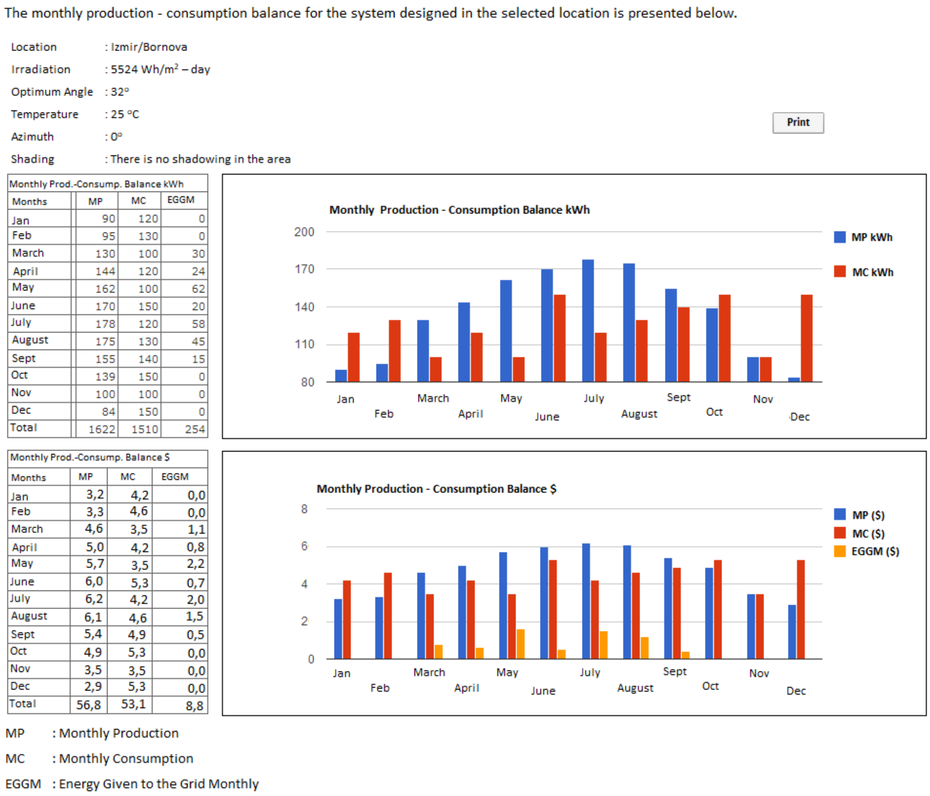
Figure 15. Dynamic data monitoring module data tracking and display screen

When the user clicks on "Reporting Module" via the Module Selection Screen, periodic reports on wind-sun and other meteorological data for the location previously selected by the user are presented to the user on this screen. When the location is selected by the user and the "Report" button is clicked on this module screen, the software asks the user for which date range, how often and what quality data they need.

The reporting of the following data, including annual, monthly, daily and hourly, can be done through this module.

- Average Radiation
- Average Wind Speed
- Average Wind Direction
- Average Temperature, Humidity, Pressure

In addition, for a wind-PV system designed and recorded with the “System Design Module” previously, the expected potential energy harvest in annual, monthly, daily and hourly periods can also be reported to the user via the “Reporting Module” as in Figure 16.


The monthly production - consumption balance for the system designed in the selected location is presented below.

Location : Izmir/Bornova
Irradiation : 5524 Wh/m² – day
Optimum Angle : 32º
Temperature : 25 ºC
Azimuth : 0º
Shading : There is no shadowing in the area

Print

Monthly Prod.-Consump. Balance kWh

Months	MP	MC	EGGM
Jan	90	120	0
Feb	95	130	0
March	130	100	30
April	144	120	24
May	162	100	62
June	170	150	20
July	178	120	58
August	175	130	45
Sept	155	140	15
Oct	139	150	0
Nov	100	100	0
Dec	84	150	0
Total	1622	1510	254

Monthly Prod.-Consump. Balance $

Months	MP	MC	EGGM
Jan	3,2	4,2	0,0
Feb	3,3	4,6	0,0
March	4,6	3,5	1,1
April	5,0	4,2	0,8
May	5,7	3,5	2,2
June	6,0	5,3	0,7
July	6,2	4,2	2,0
August	6,1	4,6	1,5
Sept	5,4	4,9	0,5
Oct	4,9	5,3	0,0
Nov	3,5	3,5	0,0
Dec	2,9	5,3	0,0
Total	56,8	53,1	8,8

MP : Monthly Production
MC : Monthly Consumption
EGGM : Energy Given to the Grid Monthly

Figure 16. Reporting module report screen

4. CONCLUSION

As an example of the output provided by the software, the static wind and solar maps produced by the General Directorate of Renewable Energy Resources in Turkey can be shown. Among these examples, only long-term data obtained from 60 wind measurement stations and meteorology stations throughout Turkey (for weather forecasting) were used for REPA. This small number of samples is insufficient to make reliable investments and precise predictions. Moreover, these existing maps are static in nature and do not rely on real-time data analysis and thus, do not have a dynamic continuity. The software developed with this study is important in that it can make calculations based on real measurement data in high resolution and that the obtained data can be observed dynamically.

The web-based software that emerged as a result of this study has a very high potential for being commercially utilized both as a finished product and an embedded tool. More than personal use, it is planned to seek a corporate membership/subscription required for access to the software. In this context, it is planned to generate user-based income from the software by converting the software into a commercial product in the future. As the target group; Large-scale system investors, Universities, System installation companies, Electricity Distribution Companies and related public institutions/organizations can be mentioned.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

NOMENCLATURE

δ : *declination angle*

β_{opt} : *optimum tilt angle*

σ : *azimuth angle*

S_{module} : *the solar radiation value on the PV panel at the tilt angle*

η_{sys} : *system efficiency*

η_{PV} : *PV panel efficiency*

η_{inv} : *invertor efficiency*

η_{bat} : *battery efficiency*

η_r : *module efficiency expressed by the module manufacturer*

β_T : *string efficiency temperature coefficient*

T_c : *average monthly cell temperature*

T_r : *reference temperature given for cell efficiency*

I_k : *total solar radiation on 1 m^2 area at the k hour of the year, kWh/m^2*

G_{PV} : *annual energy harvest of 1 m^2 photovoltaic panel*

V_r : *wind speed (m/s) to be obtained as a result of the calculation*

V_{ref} : *reference wind speed (m/s) used in the calculation*

H : *hub height (m)*

H_{ref} : *reference height (m)*

μ : *friction coefficient*

$P_W(V_r)$: *power generation of wind turbine at V_r wind speed (W)*

P_r : *rated power of wind turbine, (W)*

V_r : *wind speed at hub height (m/s)*

V_{ci} : *cut-inn wind speed, (m/s)*

V_{rated} : *wind speed at the rated power of the wind turbine, (m/s)*

V_{co} : *cut-out wind speed, (m/s)*

V_i : *wind speed to be calculated (m/s)*

V_{ave} : *average wind speed (m/s)*

h_r : *daily blowing time (h)*

$h_{r,i,j}$: *wind blowing time at i m/s wind speed at j hour of the year*

C_p : *wind turbine power coefficient*

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