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GRADO EN INGENIERÍA EN TECNOLOGÍAS DE TELECOMUNICACIÓN

TRABAJO FIN DE GRADO

SIZING OF INSTALLED CAPACITY OF SOLAR PHOTOVOLTAIC PLANTS FOR HOUSEHOLDS

Autor: Javier González-Guerrero García

Director: Slavko Krajcar

Co-Director: Lin Herenčić

Madrid

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"Sizing of installed capacity of solar photovoltaic plants for – households"

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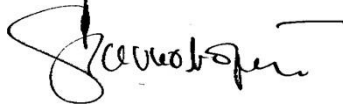
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Madrid

Abstract

Author: González-Guerrero García, Javier
Supervisor: Krajcar, Slavko; Herenčić, Lin
Colaborating organization: ICAI – Universidad Pontificia de Comillas and FER – University of Zagreb

The installation of solar photovoltaic power plants used to be highly supported by public supporting schemes. Today, decreasing costs of solar power plants allow minimization of state aid and installations are becoming cost-competitive. However, final cost-effectiveness depends on many factors that are specific for each location. The main objective of this project is to develop and test a tool, that demonstrates if a solar photovoltaic investment for a household is feasible or not in The Republic of Croatia. Thus, this paper is focused on the variables that have to be taken into account when designing a particular installation.

The work included gathering and analyzing data on energy consumption, production, and the features of the solar panel brands. Further, all the information was grouped into software Matlab. Finally, according to the Croatian legal framework on renewable energy sources, the tool was developed. As a result, the main economic indicators can be calculated and it is possible to discover the most efficient option when sizing the solar power plant for a particular household. In this sense, the tool is very flexible. The project tests and creates a ranking among the different brands, but it also can be used as a comparison tool.

The case study analysis showed that Croatia is a country where particular solar investments can be feasible if certain conditions are met, such as the use of energy on the location of production, adequate solar irradiance, and rightly sized number of panels.

Key-words: solar power, photovoltaic, installed capacity, Croatia, investment, household, feasibility, own-consumption.

Resumen

Autor: González-Guerrero García, Javier

Supervisor: Krajcar, Slavko; Herenčić, Lin

Organizaciones colaboradoras: ICAI – Universidad Pontificia de Comillas and FER – University of Zagreb

El objetivo principal del proyecto es desarrollar y probar una herramienta que demuestre si una inversión solar fotovoltaica para un hogar es factible o no en la República de Croacia. En consecuencia, algunas marcas con diferentes características crearán una muestra que se analizará de forma independiente de acuerdo con algunos parámetros económicos.

Por lo tanto, este documento se centrará en las principales variables que deben tenerse en cuenta al diseñar una instalación en particular. El procedimiento comenzó reuniendo toda la información sobre el consumo de energía, la producción y todas las características de las marcas de paneles solares. Después de esto, toda la información fue agrupada en Matlab.

Finalmente, al usar la ley croata en torno a las energías renovables y los principales indicadores económicos, es posible descubrir la opción más eficiente al instalar paneles.

Por otro lado, el proyecto demostrará por qué la Prima de Incentivación (FiT) es la variable importante, a fin de decidir si el inversor debe usar su instalación para ahorrar o ganar dinero a largo plazo. Croacia es un país donde se deben realizar inversiones solares particulares para ahorrar dinero, y se realizó un cálculo del número más preciso de paneles.

En este sentido, la herramienta es muy flexible.

 El proyecto prueba y crea un ranking entre las diferentes marcas, pero también puede usarse como una herramienta de comparación. Tanto es así que se demuestra que instalar más de 4 paneles de media, se traduce en una mala inversión con un VAN negativo.

Palabras clave: Fotovoltáico, capacidad instalada, Croacia, Inversión, Hogar, Solar, Fiable, Energía

Acknowledgment

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List of Acronyms

AC: Altern Current

CSP: Concentrated Solar Power

DC: Direct Current

DIF: Diffuse Horizontal Irradiance

DNI: Direct Normal Irradiance

FiT: Feed-in-Tariff

GHI: Global Horizontal Irradiance

HRK: Croatian Kuna, the main currency

IEA: International Energy Agency

IRR: Internal Rate of Return

NPV: Net Present Value

PP: Payback Period

PV: Photovoltaic

STC: Standard Test Conditions

W: Watt

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INTRODUCTION

1. INTRODUCTION

1.1. OBJECTIVE

The aim of the project is to design a programming tool, which allows the user to know whether a solar panel investment for his own house in The Republic of Croatia is worth the costs or not.

This tool will consider some of the multiple input variables that take part into the solar energy production process, in order to create a realistic model.

Moreover, this tool, will also choose the best option between different Solar panel models that are available in the market to obtain the main variables that take part in the project and to help the user in his decision

1.2. MOTIVATION

In recent years, a general concern has irrupted in our society, and this concern is about the future of energy production. Most of the energy produced in our world comes from polluting sources such as fossil fuels or uranium. They all produce waste in several ways

Nowadays, everybody is getting closer and closer to the idea that the future of energy production lies in renewable sources. The most commonly used ones are water, wind, and sun. This last source is the one that more prospect has, and the main reason is the self-production capacity.

There is a new stakeholder in terms of energy production, and it is usually called "*prosumer*". Prosumer is both, energy producer and energy consumer, citizen, or company that can generate energy in their own house or another building, and use it or trades it in the energy market.

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This fact opens the door to a new vision of the market regarding energy. Now the consumer can save money and build a more environmentally friendly world.

In this sense, my motivation for this project is to help society to keep changing the world in a more sustainable path. Not only because of the world itself but also because of all the illnesses created by non-renewable sources. I think that if any affluent citizen saw that he could save money in the long term by just installing some panels on his rooftop, he would probably do it

1.3. GLOBAL SOLAR POWER INDUSTRY

There are two types of solar power generation: Photovoltaic Solar Technology (PV) and Concentrated Solar Power (CSP). The project will just be focused on the first ones because it´s the only one among them that can be deployed in households.

For the last two decades, photovoltaic plants have become a mainstream electricity source. So is that, that world`s solar photovoltaic installed capacity has grown exponentially. Moreover, Photovoltaic solar energy production increased by 31% in 2018, representing the largest generation growth regarding renewables (+136TWh). In Figure 1, exponential growth of PV can be seen, and if the tendency remains, in 2030 PV installed capacity will be higher than 3000 TWh.(IEA,2020)

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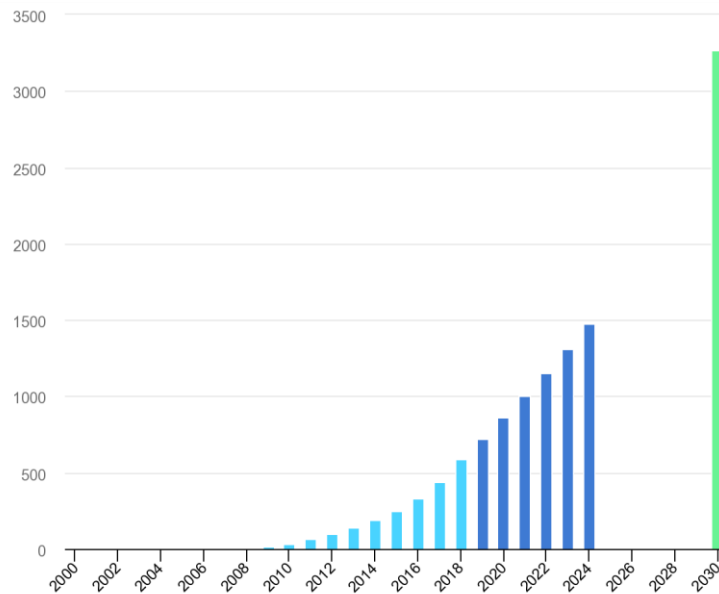
Figure 1 - Solar PV energy generation (TWh) in the Sustainable Development Scenario, 2000-2030(IEA, 2020)

There are many reasons for this growth (Irena,2019), among them:

- Global energy decarbonization: The Paris Agreement stated that the limit of temperature rise had to be below 2ºC, ideally 1.5ºC;

- Deployment of rooftop solar photovoltaic systems for distributed generation: The global installed capacity on rooftops, is approximately 43GW (IEA, 2018). The leading country is China, where 47% of installed capacity in 2018 was for this purpose; and

- Solar PV for off-grid solution: sun power provides an easy way to obtain energy without depending on the grid, 85% of off-grid installations are PV. This is usually performed when the costs of grid connection are high.

All these reasons, along with the constant improvement of panels, which has reduced its costs by 74% since commercialization, explain the importance of this technology.

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Despite all the benefits, deeper research has to be developed when designing a rooftop installation. This research will mainly depend on the country, especially the sun hours during the day and the country`s market structure.

1.4. CROATIAN SOLAR POWER INDUSTRY

The Republic of Croatia is a country where renewable energies have enormous potential. According to the Government, renewables consumption will represent 36.4% of national consumption.

Nowadays, almost half of energy production is hydropower energy (49.56%), while almost the rest of the production is thermal energy, including the imported nuclear energy from Slovenia (Krško PP). The high polluting production and the needs of energy importation are important factors for changing the whole energy production structure.

Another important factor to change the market of energy is the meteorological conditions. The most important variable when designing a PV is "Sun-hours". Croatia is one of the best countries in Europe in terms of sun hours, for instance, Spain, Italy or Greece are also good countries to develop this technology.

All these reasons cause an important impact on Croatian`s Energy current structure. It is hoped that renewable installed capacity raises up to 1.9 GW in 2030 (Global Data).

1.5. PROJECT STRUCTURE

The structure of the paper will be as following:

- Firstly, the environment around solar panels will be discussed. In this section, the historical background, the main solar panel theory, and the solar energy market will be the target;

- Secondly, a panel nameplate will be explained, and the main aspects that influence the selection of brands. The main input variables will be also explained in this section;

- In the next part, the consumption and production patterns will be explained. Here all the chosen hypotheses will be presented;

- Then, an analysis of results will be developed, in terms of energy production and investment risks using the created model; and

- Finally, a general conclusion will be added. Also, some improvement tips will be found in this space.

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TECHNOLOGY DESCRIPTION

2. TECHNOLOGY DESCRIPTION

The main technology that was used in this project was Matlab R2018b. All the programming tool was developed using this software. Some of the figures have also been created with it.

Apart from this commonly used software, two more useful software was used:

- **LoadProfileGenerator [1]**: this tool generates any kind of residential consumption model. After considering some functional patterns, it generates CSV with the energy consumption hourly, along the year.

- **Renewables.Ninja [2] [3]**: this software provides the user's vision of the meteorological conditions in the selected place. Some of these aspects are the irradiance or the temperature. These figures will also be given hourly and in CSV format.

- **Excel:** creates all the necessary information and samples in the project. All the structures in Matlab are based on excel files.

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SOLAR ENERGY ENVIRONMENT

3. SOLAR ENERGY ENVIRONMENT

3.1. HISTORICAL BACKGROUND

In 1839 Edmond Becquerel built the first photovoltaic cell, and he managed to experimentally demonstrate the photovoltaic cell.

After that, a lot of attempts on developing solar technology were made, but it was not until 1954 when Daryl Chapin, Calvin Fuller, and Gerald Pearson developed the silicon photovoltaic (PV) cell at Bell Labs. Those cells could achieve an efficiency of 4%.

Five years later, the first commercially available cells with 10% efficiency were created. However, those cells could just be mainly used for industrial purposes because of the fact that cell costs were 100$/W. This situation changed in 1970 when the improvement of these cells reduced the effective costs to 20$/W. At this time first domestic solar applications began to appear all around the world, mostly in remote locations where grid connection was really difficult.

Prices have constantly fallen down, due to efficiency improvements (around 20%) and production cost reductions, until 2019 price which was approximately 2.96$/W according to Figure 2 (IEA,2020). These prices are manageable for households, in order to invest in this technology, and creates an opportunity for them to save money in the long term. Furthermore, governments are nowadays offering loans and support to encourage citizens to incorporate this technology into their houses.

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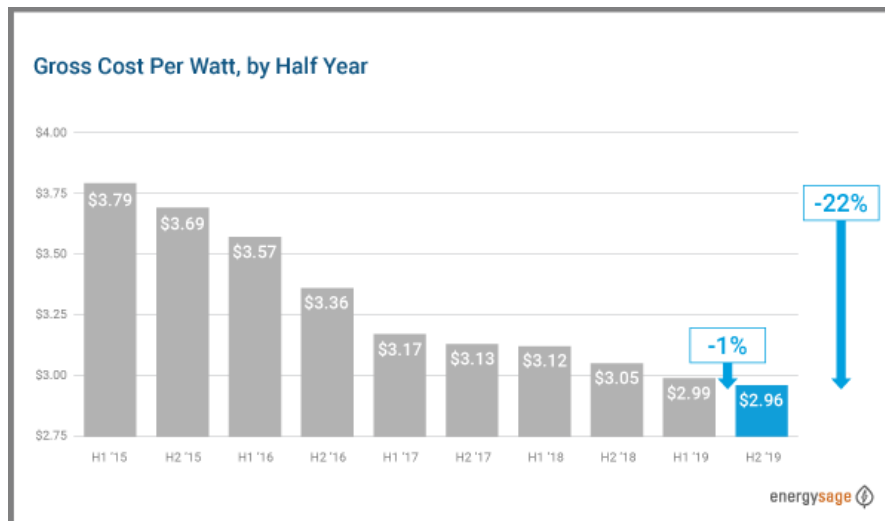
Figure 2 – Cost-per-watt evolution, 2015-2019(IEA, 2020)

In 2017 a group of U.S. scientists developed a prototype of solar cells capable of 44.5% efficiency, that is why there is an optimistic vision around the future of solar energy and generates interest.

So to sum up, photovoltaic technology has improved in a really good way, and the tendency seems to keep raising cell efficiency while costs will keep on decreasing. The latest average cost-per-watt is around 1$

3.2. THEORY OF PHOTOVOLTAICS

A solar cell works based on the photovoltaic effect. This effect occurs when two different semiconductor materials are in contact in the presence of an external agent (light or radiation mostly). When light hits the material, an electron is freed a voltage difference is created, and the current can now flow through the panel. The materials used are different depending on the type of panel, but Silicon is the prime semiconductor.

The electricity created by the photovoltaic effect will be DC. Several solar cells form a panel and by connecting several solar cells in series or parallel a higher voltage can be created according to the panel necessities.

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Before talking about the characteristics of solar panels, it is necessary to underline that in order to compare panels between them, these are the STC values (standard test conditions), which are:

- irradiance: 1kW/m^2,

- air mass: 1.5 (sun angle), and

- cell temperature: 25ºC.

The most important characteristics when talking about panels are the peak-voltage, the peak-current, and peak-wattage. The last one is the maximum power that can be obtained from a solar panel in STC conditions, the main equation that links them is Equation 1:

$$W_p = U_p * I_p$$

(1)

Where,

W_p: peak-wattage (W)

U_p: peak voltage (V)

I_p: peak-current (A)

Another important issue when talking about photovoltaics is the Solar Irradiance or Irradiation, which is defined as the power of solar electromagnetic radiation received by a surface per area unit (W/m^2), and it is the main key to obtain a higher or lower energy output. There are three kinds of solar irradiance: Global Horizontal Irradiance (GHI), Diffuse Horizontal Irradiance (DIF), and Direct Normal Irradiance (DNI). They are linked with Equation 2 (Dr. Sanjay Vashishtha, 2012):

$$H_T = GHI = DNI * \cos(z) + DIF$$

(2)

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Where,

H_T: Global Horizontal Irradiance (W/m^2)[1]

z: zenith angle

In order to know whether a country is good for installing panels or not, the Global Solar Irradiation as the annual average of the global horizontal irradiation, H0 is defined. In the Republic of Croatia, this value is 1350 kWh/m^2. For instance, Madrid has 1825 kWh/m^2 and Berlin 1022 kWh/m^2

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[1] SI system recognices Ee or I refering for Irradiance, but in this project Energy and Current have those sysmbols. H will represent Irradiance

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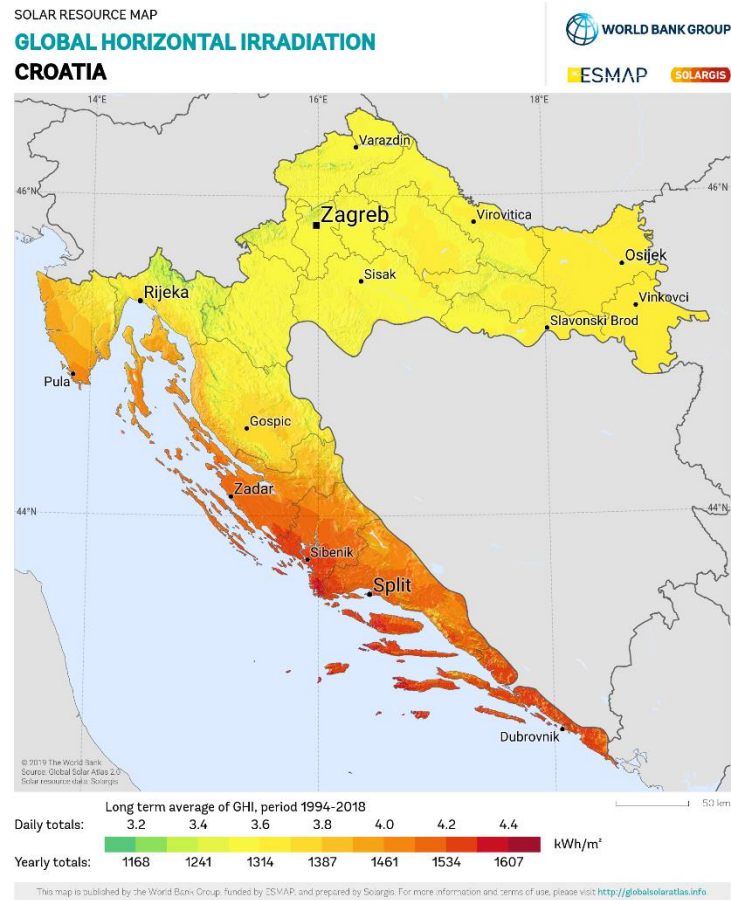
Figure 3 -Solar Irradiation in The Republic of Croatia (Solaris)

Regarding Irradiance, a more accurate formula to measure sun irradiance is used, these are the Peak sun hours, which is defined in Equation 3:

$$SH_p = \frac{H_0}{H_{stc} * 365} = \frac{H_d}{H_{stc}}$$

(3)

Where,

SH_p: peak-sun hours, runs from (0,24), in hours/day

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H_d:Daily Global Horizontal Irradiance, the average daily irradiance for an specific location, (W/m^2)/day

H_0: Annual Global Horizontal Irradiance, the average annual irradiance, (W/m^2)/year

H_{stc}: Irradiance Standard Test Value, (W/m^2)

The panel efficiency is also a really important issue when talking about energy production along with latitude and climate.

The solar panel efficiency depends on the materials used (this includes the type of panel), the glass reflectance efficiency (the less reflection, the better), and the thermodynamical efficiency (around 86%, after that, sun energy turns into heat, not electricity).

Currently, the market`s panel efficiencies are around 20%. This number has increased by 0.5%/year since 2010, and it still tends to grow.

Once the main parameters have been defined, another formula can be defined to obtain the peak-wattage of "n" panels can be seen in Equation 4 (Toll, 2017):

$$W_p = H_{stc} * A * \eta_p * n$$

(4)

Where,

A: Area of the panel, $[m^2]$

η_p: nominal Efficiency of the panel, [%]

n: number of panels,[-]

The produced energy by "n" panels in 1 hour can be defined in Equation 5 (A Kazem, Khatib, Sopian;2013):

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$$E = H_T * A * \eta_p * n$$

(5)

Where,

H_T: it is the Global Solar Irradiance obtained in a specific hour T, [W/m^2]

E: Electrical Energy obtained by the n panels in hour T, [W]

If the Area from equation 4 is subtracted and combined with the produced energy, in equation 5, a formula which uses the Peak-sun hours can be obtained in Equation 6 (Toll, 2017):

$$A = \frac{W_p}{H_{stc} * \eta_p * n}$$

$$E = SH_p * W_p * n = \frac{\sum_{t=1}^{24} H_T}{H_{stc}} * W_p * n$$

(6)

Where, $\sum_{t=1}^{24} H_T = H_d$,is the sum of the daily irradiance.

Equation (6) demonstrates why the peak sun hours are important. This formula is a general approximation to avoid most of the variables except the peak-wattage, and calculate the necessary number of panels "n" without much calculation.

3.3. TYPES OF SOLAR PANELS

There are mainly three types of solar panels, according to their shape and characteristics. These types are Thin-film, Monocrystalline and polycrystalline solar panels. In this section all of them will be described and compared in order to know which one is better for households:

Thin-film panels

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These panels are made of multiple materials. The most commonly used ones are those made of cadmium telluride (CdTe). Other thin-film panels are made of Copper Indium Gallium Selenide (CIGS) or amorphous silicon (a-Si)

They are the thinnest panels in the market and their efficiencies reach 11%. Their capacity is small due to their small dimensions.

However, they are much cheaper to produce and installation costs are lower than for the other type of panels.

Monocrystalline panels

These panels are made of a pure silicon crystal, and that gives them a black color.

Most Monocrystalline solar panels can easily reach efficiencies higher than 20%, which makes them the best panels in the market.

On the contrary, their prices are also the highest among all the types.

Polycrystalline/Multi-crystalline panels

The last of the main solar panel types have the best quality-price ratio. They are also made of silicon, but with fragments than have been melted together. This process gives them a bluish aspect.

Their efficiencies go between 15% and 17%, because of the fact that electrons are not able to move so easily like in a pure silicon wafer.

As mentioned, their prices are lower than Monocrystalline panels, due to an easier production process.

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Table 1-Comparison between types of panels

Type	Material	Efficiency	Price	Longevity
Thin-film	CdTe/CIGS/ a-Si	~11%	$	15 years
Monocrystalline	Silicon Crystal	>20%	$$$	+25 years
Polycrystalline	Silicon fragments	15%-17%	$$	+25 years

3.4. TYPES OF LOSSES

Solar energy is a technology that depends on meteorological and physical conditions, mainly the sun and the clouds.

It is also a technology that produces DC current. Most of the devices available for households require AC current, this issue is solved by adding a DC/AC inverter and a transformer.

Because of these reasons, producing solar energy results in energy losses, that have to be taken into account when calculating generated energy. These losses are grouped into 3 types.

Firstly, Pre-Module losses are the ones that depend on meteorological conditions. Dirt, snow, shading, or reflection are the main Pre-Module losses. Power tolerance is also included in this section, the production is never as stated on the datasheet. Manufacturers provide tolerance of 5%.

The second category is called Module losses, they include the nominal efficiency, which is written in the datasheet for standard conditions and Thermal losses.

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Thirdly, System losses have to be taken into account. These losses are electricity losses caused by AC and DC wires, inverters. and the transformer that is connected to the grid. They are generally around 14% and they are included in the energy production in Equation 7, which makes Equation 5 results more realistic and accurate:

$$E = H_T * A * \eta_p * n * \eta_s$$

(7)

Where, η_s are the System losses, in [%]

There are also losses caused by maintenance and lack of operation, even though panels rarely require them, but generally, Equation 7 will be the used one.

3.5. CROATIAN SOLAR MARKET DESCRIPTION

The most important thing that has to be studied before installing solar panels is the climate and therefore the peak sun hours, Croatia as it has been explained before is a good country in terms of solar conditions. But it is also really important to examine the market environment before investing in solar energy.

The most important concept of the solar economy is the Feed-in Tariffs (FiT), which is one of the policy tool to promote investments in PV. It consists on paying an above market price to the producer for the produced energy surplus that goes to the grid. FiT is offered in long-term contracts from 15 to 20 years. They were invented in 1978 in the United States, but they are now widely used.

It is important to mention that in Croatia there is no FiT for small PV. This fact means that there will not be a high benefit when installing panels, instead, the benefit will be the energy savings caused by self-consumption. There are sometimes grants, but rarely for households.

The revised [Law on RES](#) in Art 44. defines setup for small prosumers. There are differences between industry and household sectors.

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For households in each month:

- households pay for:

$$\left(E_{imported} - E_{exported}\right) * \left(C_{energy} + C_{other\ levies}\right)$$

- if Energy exported > Energy imported, suppliers take the surplus for a price of $C_{energy} * 0.8$; and

- Also, if in a year Energy exported > Energy imported, the rules apply as for the industry sector prosumers.

Industry sector prosumers in each hour:

- Subjects pay for:

$$E_{imported} * \left(C_{energy} + C_{other\ levies}\right)$$

- Subjects receive for energy exported: $C_{energy} * 0.9$; and

- If in any month Energy exported > Energy imported, for exported energy subjects receive:

$$C_{energy} * 0.9 * \frac{E_{imported}}{E_{exported}}$$

Generally, the biggest savings are if the energy is mainly used for self-consumption – that is why it is important that systems are seized good for consumption.

Cost for energy for households is roughly 0,4 HRK/kWh, while the cost for other levies (transmission, distribution, taxes, contributions) is also around 0.4 HRK/kWh, meaning that total cost is around 0.8 HRK/kWh.[2]

---

[2] $1 HRK \approx 0.13€$

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TOOL DEVELOPMENT

4. TOOL DEVELOPMENT

4.1. SYSTEM ANALYSIS

The goal of the developed tool is to study the feasibility of solar PV. The most important aspects that have been studied before designing the tool are the consumption patterns, production patterns, and the sampling of brands that will be studied.

4.2. SAMPLE

Sampling is the first step in order to evaluate the feasibility of a PV plant. Currently, solar technology is advancing exponentially with higher efficiencies and lower prices. Those are the main reasons in order to know if an investment will be successful or not. The main characteristics that have been studied among the different brands are mainly:

- Wattage-peak (W);

- Panel efficiency (%);

- Type of panel: Thin-film, Monocrystalline, Polycrystalline;

- Cost-per-watt ($/W);

- Temperature Coefficient (%/ºC); and

- Warranted annual performance degradation runs from year 2-25(%/year).

4.2.1. CONSUMPTION

The installation of solar PV in households looks for covering the whole consumption needs of it. However, every household has its own consumption quantities, and the number of installed panels will vary according to those quantities.

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In this project, the first hypothesis that has been used is a constant consumption pattern over the years. This pattern is based on an average European couple, whose members work and use the usual household devices such as a washing machine or a router.

In Figure 4, it can be seen that August and December are the months where consumption has been the highest among them. In figure 5, the observer can see the average energy consumed during different day hours. 8 p.m. is the most critical hour, special attention needs to be paid.
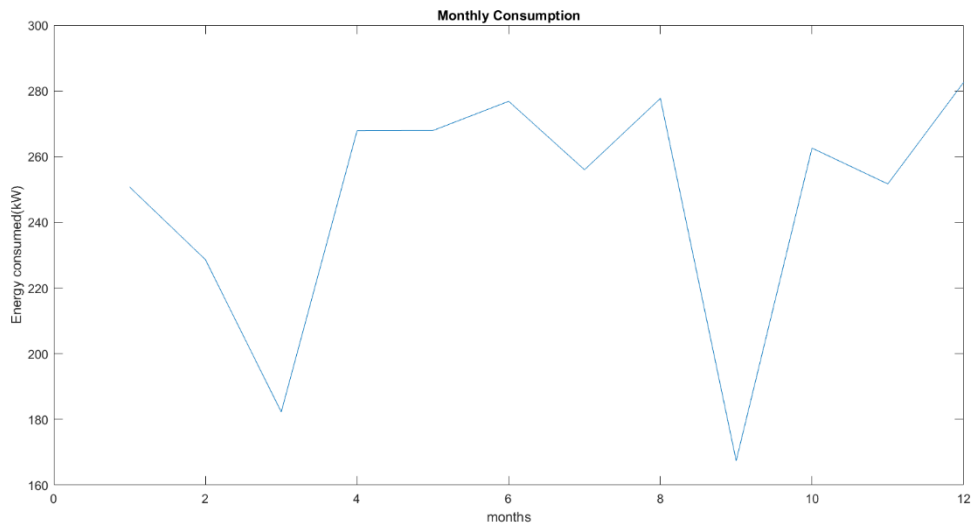
Figure 4 – Monthly Total consumption during a year according to the model(IEA, 2020)

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TOOL DEVELOPMENT
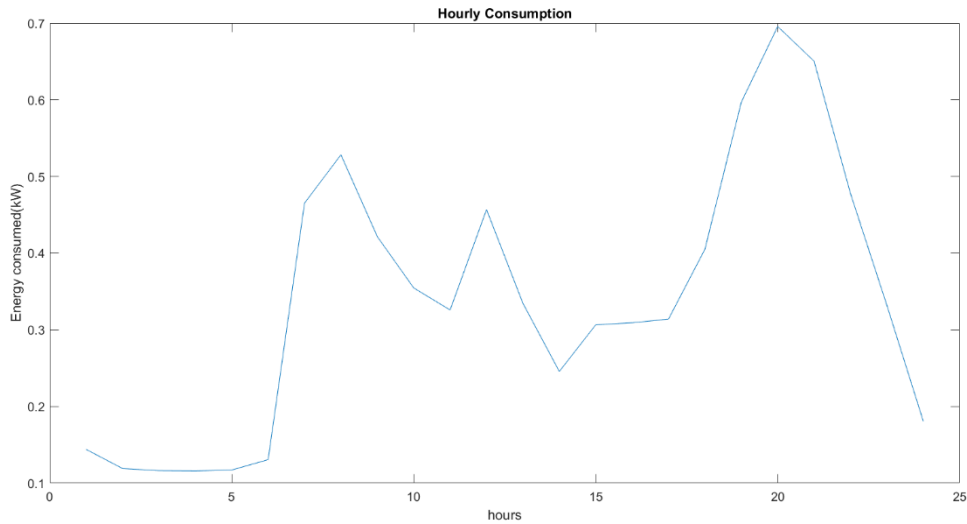
Figure 5 – Hourly mean consumption according to the model

4.2.2. PRODUCTION

This section is the key point in order to develop the programming tool. While using the tool, 3 input variables will be asked to the user:

- The desired number of panels;

- The tilt of those panels ; and

- The system losses that those panels will have to face.

In order to know how many panels, the following calculation has to be made:

$$n = \frac{E_{d,cons} * f}{SH_p * W_p}$$

(8)

Where,

$E_{d,cons}$: is the daily consumption of a household, [W]

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Tool development

f: security factor so that the number of necessary panels can cover an excess of consumption, [-].

This formula will provide the necessary number of panels for the household to cover the whole household consumption, by assuming mean daily values throughout the year.

From Figure 6,which is a daily Irradiance chart, it is obtained that the daily average consumption is:

$$E_d = \sum_{t=0}^{24} E_T = 8.1426 \; kWh/day$$

In Figure 6, a daily maximum can be found at around 12p.m .From the Irradiance chart, the peak sun hours can be obtained
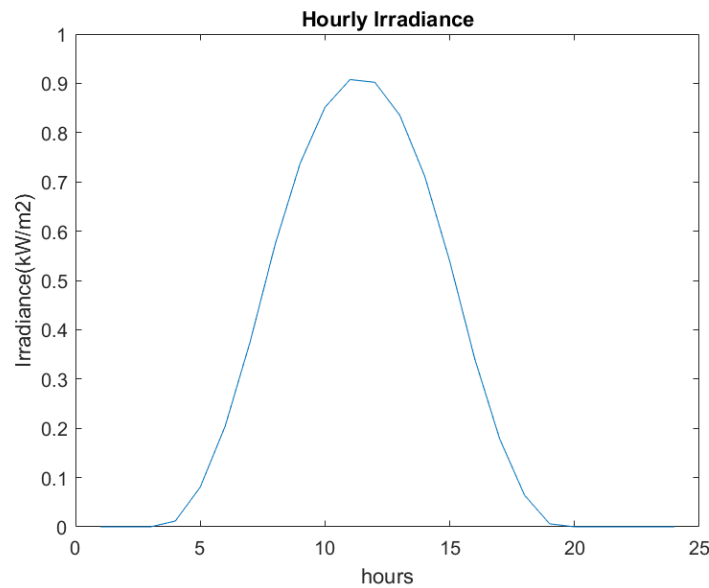
Figure 6 – Hourly mean Irradiance during a day in the Republic of Croatia.

From Figure 6 and also subtracting the number of panels in Equation 6, it is obtained that the sun peak hours are:

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$$H_d = \sum_{t=0}^{24} H_T = 7317.5 \frac{Wh}{m^2}/day$$

$$SH_p = \frac{H_d}{H_{stc}} = 7.3175$$

Finally, from the brands market sample the average peak-wattage obtained is

$$.W_{p\,avg} = 326.29W$$

With all the average values, and with a security factor of 20%, f=1.2

$$n = \frac{E_{cons} * f}{SH_p * W_p} = \frac{8142.6 * 1.2}{7.3175 * 326.29} = 4.09 \approx 4\ panels$$

This means that installing four panels will be enough to cover the whole consumption, and even getting to obtain some extra profit.

4.3. DESIGN

The program will first ask the user for the input variables: the number of panels desired, panels tilt, and the system losses.

The second step will be to find out the power output and the investment costs from every solar panel in the sample.

Once that part is done, the system will analyse every brand separately in terms of economic issues, such as Net Present Value, Internal Rate of Return, and Payback Period.

Three variables will be calculated from each brand, which are the main economic indicators:

- NPV: this variable is the main indicator that will tell the user if his investment will be profitable in the stated years. If NPV>0 the user should accept the project:

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$$NPV = -I_0 + \sum_{y=1}^{Y} \frac{B_y}{(1+i)^y}$$

(9)

Where,

I_0: is the initial investment that has to be done regarding panels and installation.

B_y: is the net benefit that is obtained by the prosumer in year "y"

i: is the discount rate of return that could be earned with the investment.

Y: is the number of years (time periods) for the investment

- IRR: the discount rate that makes the NPV equal to 0, the higher it is the better:

$$NPV = 0 = -I_0 + \sum_{y=1}^{Y} \frac{B_y}{(1+IRR)^y}$$

(10)

- Payback period: it is the most visual, but also the most inaccurate economical metric. It is the ratio between the initial investment and the benefit obtained in the first years, and the result is the number of years in which the initial investment will be covered. It is inaccurate, because it doesn't take into account the benefit bias among the different years, so this method fails to account for the time value of money:

$$PP = \frac{I_0}{B_1}$$

(11)

Being NPV, the most accurate of them all, the algorithm will return the user the results of the brand with the highest NPV among all of them.

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TOOL DEVELOPMENT

4.4. *IMPLEMENTATION AND HYPOTHESES*

Solar technology depends on a lot of variables, and to simplify that complex job, some assumptions and hypotheses have been made.

Some input variables in the real world that have not been taken into account:

- Latitude: it is a really important magnitude to obtain the maximum power output possible. For countries in the north hemisphere, panels should be facing South.

Panels should be facing North in the case of the South hemisphere.

The first assumption that was made is that the panels in the simulation are facing south, since the project was designed for this country:

- Meteorological phenomenon such as clouds, shadings, dirt or pollution. The second assumption that has been made in this project is that those meteorological factors are included in the Irradiance output; and

- Type of panel: For instance, reflectance is not the same for a Monocrystalline and a Polycrystalline panel. Those losses have been assumed to be included in the efficiency of the panel.

Furthermore, some more hypotheses have been made:

- The whole program has been designed for a determined model of household, another lifestyle and number of members may vary the whole calculations;

- Consumption has been assumed constant during the years; and

- Fixed costs such as operation, inverter, cables or maintenance have been supposed constant for every brand due to a lack of information. This means that the only variable that will affect the price of the installation will be the cost-per-watt, independent for every brand.

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TESTS AND RESULTS

5. TESTS AND RESULTS

Once the whole system has been described, the program will be compiled considering the following input variables:

- Number of panels, n=4;

- Tilt=0º. This means that the model assumes that the sun rays are always perpendicular to the panel, the most optimistic model;

- System losses, $\eta_s = 14\%$, according to the average market values; and

- The periods planned are 25 years, when most of the guarantees expire.

The first output the program will give can be seen in Figure 7 an Figure 8, is the power output and costs graphs of all brands:
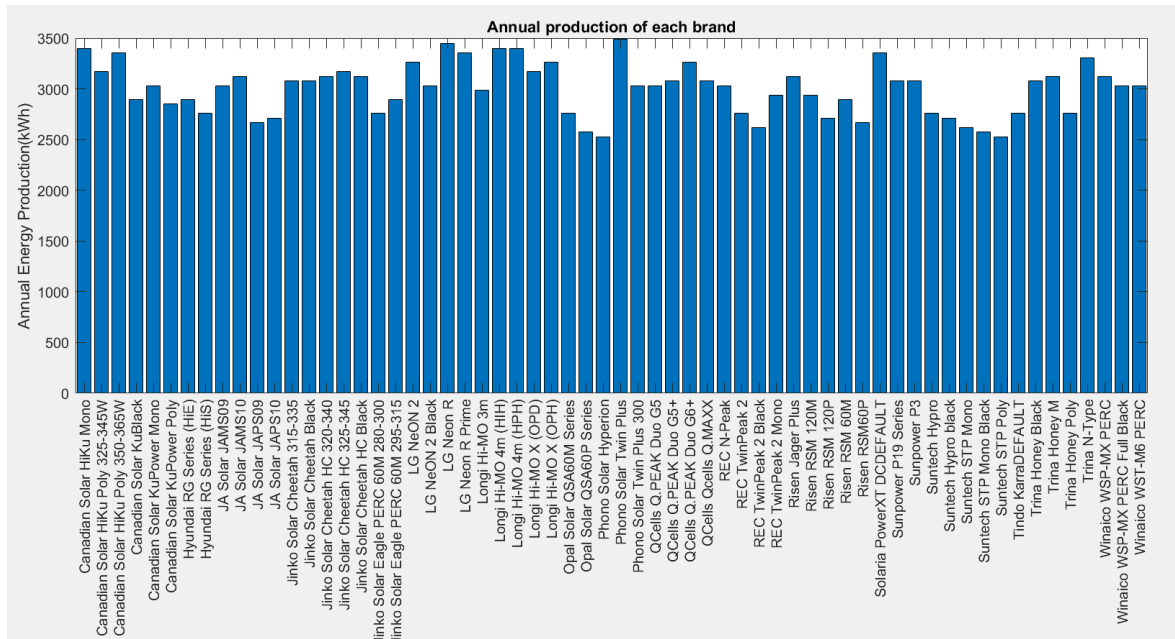
Figure 7 – Annual Solar Energy Production of each brand

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TESTS AND RESULTS
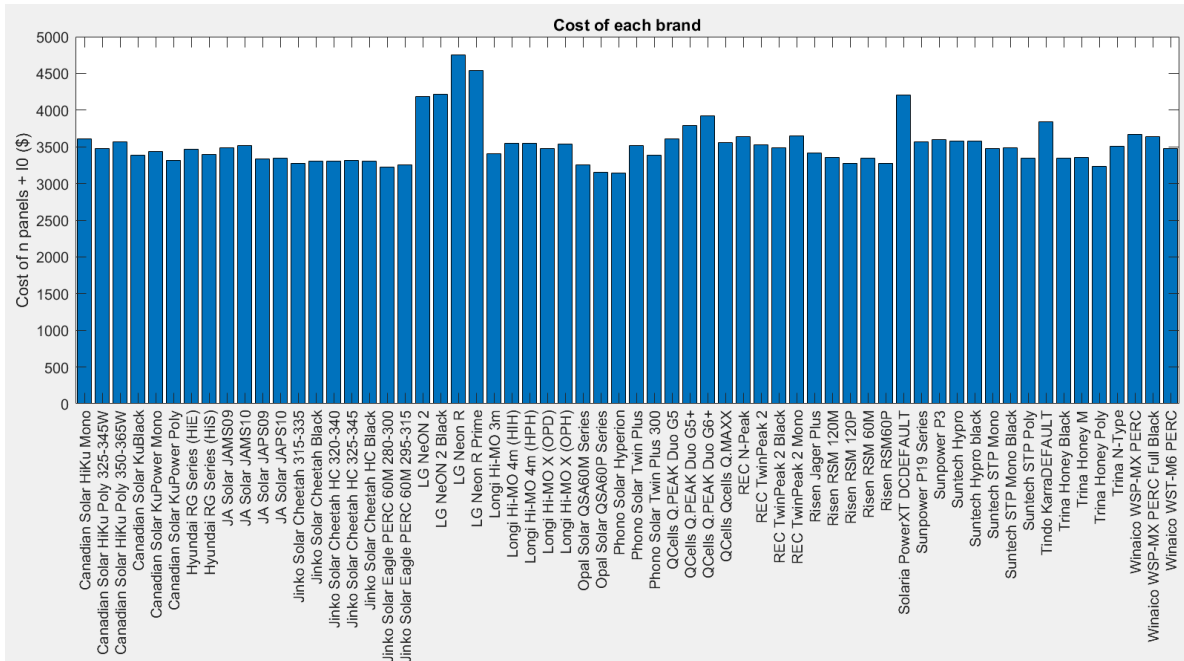
Figure 8 -Fixed costs of each brand

Figure 7 and Figure 8 are a valuable way to see the quality-price ratio, but deeper research has to be done. It can be seen that most of the panels available have very competitive energy production numbers, but the prices tend to vary among brands.

In order to increase the tool`s accuracy, two more variables have been taken into account.

- Temperature coefficient: The panel production is lower if the operation temperature is higher, every brand has its own coefficient; and

- Warranted annual performance degradation: Every panel sees its own efficiency affected over the years.

Now the main economic measures take part in the tool. According to the analysis, the brand that is more beneficial to the user is ''Canadian Solar KuPower Poly''

NPV	PP	IRR
1170.5	10.505	0.072006

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TESTS AND RESULTS

The program will also provide an estimation of the best brand in terms of production and consumption.
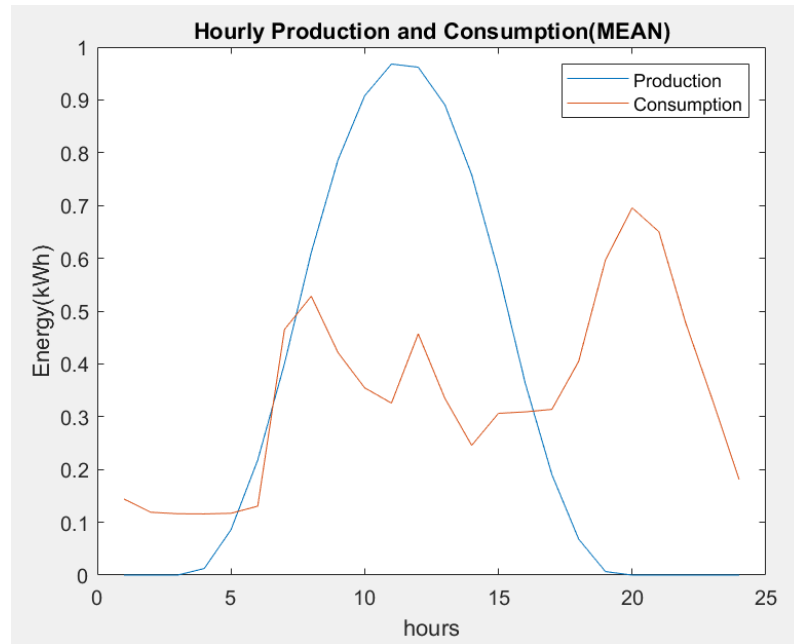
Figure 9 – Mean Hourly Production and consumption patterns during a day

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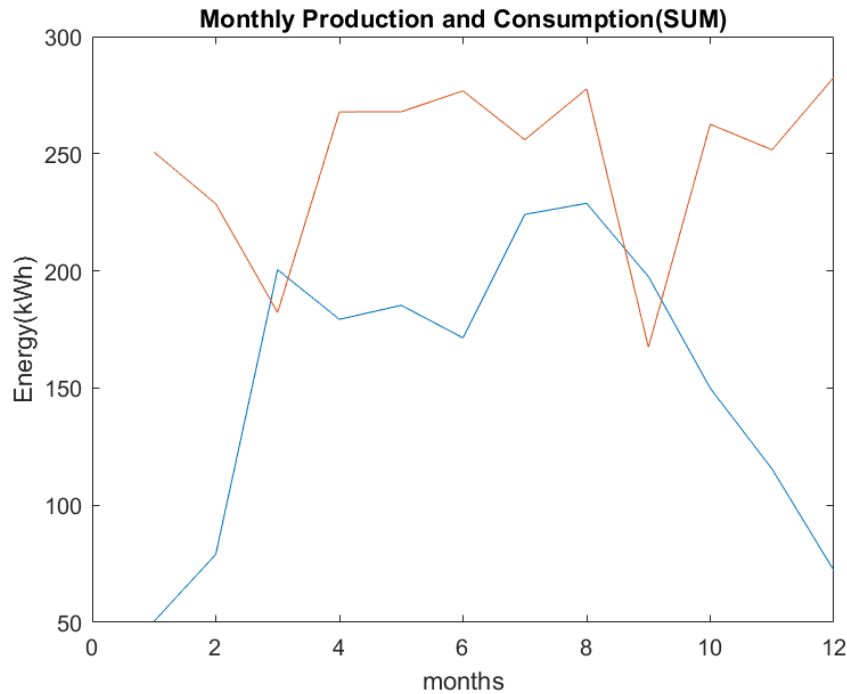
Figure 10 – Monthly production and consumption sum during a year

In addition, the program will offer the user a graph that states the energy output that can be obtained for the most suitable panel with a different number of panels in a ± 2 range, to show more options, it can be seen in Figure 10. There a lineal block diagram shows that four panels are the minimum limit to create a reasonable benefit up to 25 years.

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TESTS AND RESULTS
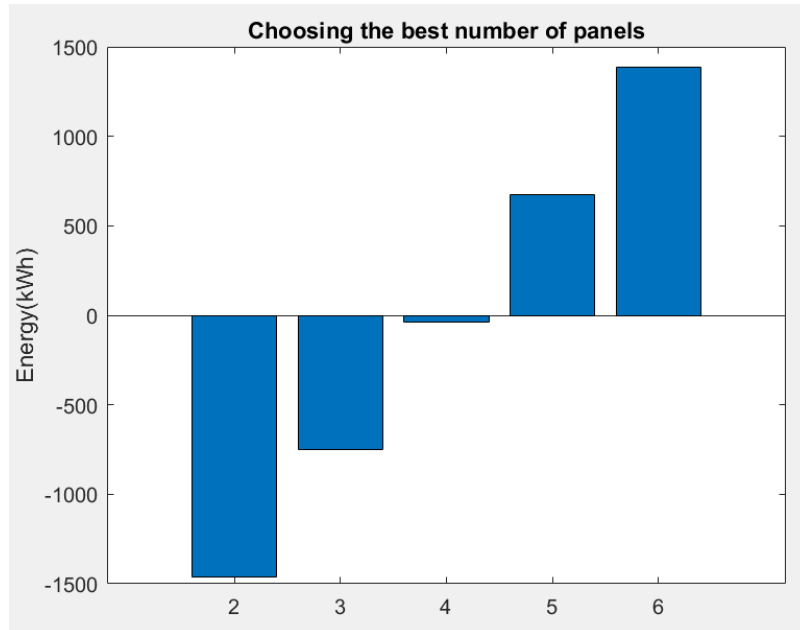
Figure 11– Annual energy production estimation depending on the number of panels

There is also another issue that has to be taken into account. As mentioned the best way to use solar technology in Croatia is by saving money. If the user chooses to sell the whole amount of produced energy, consumption goes to 0Wh, but on the other hand, incomes are much higher. In Figure 12, it can be seen that if the whole solar power obtained is sold to the grid, the incomes have a lower slope, and for that a lower benefit on time. That is why the Feed-in_tariff has an important role in solar market decisions. Payback period is also reached before, when saving money.

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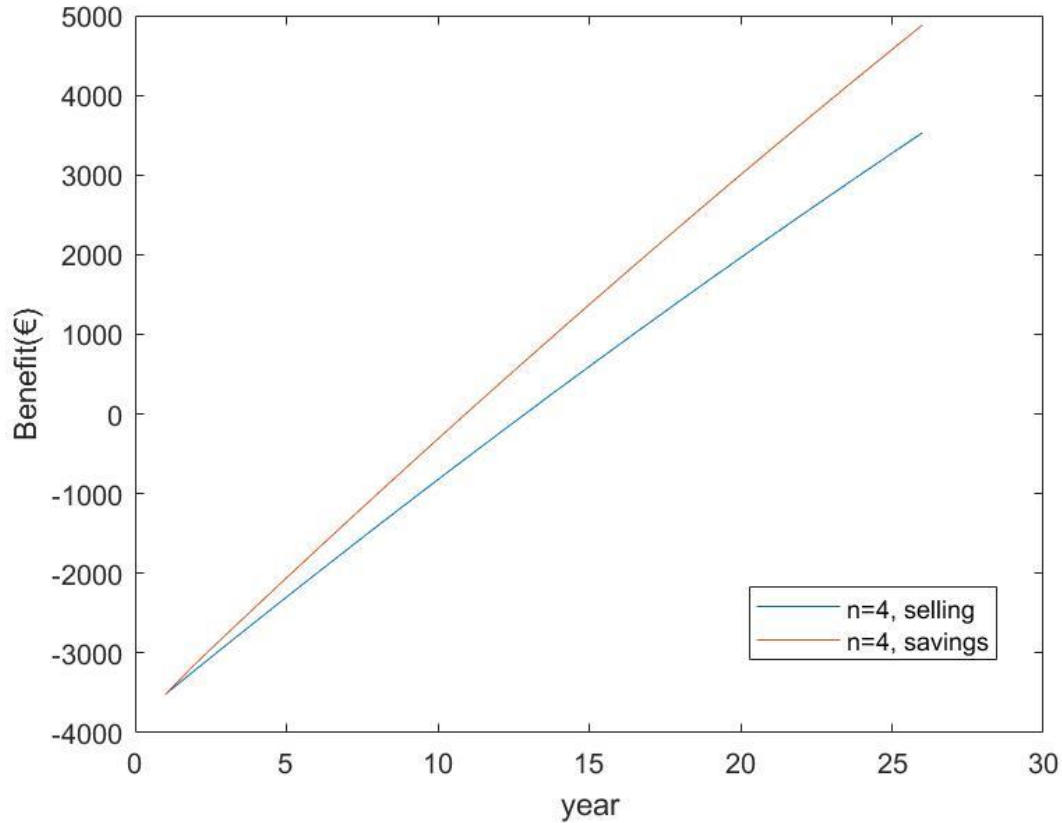
Figure 12 – Benefit Comparison between selling and saving with 4 panels

Figure 12 demonstrates that Feed-in-Tariff is the most important indicator to choose between saving and selling. The best option in the Republic of Croatia is to use the Energy for self-consumption and with the minimum number of necessary panels.

This project also demonstrates the Feed-in-Tariff issue in Figure 13, where it can be clearly seen that the best option of panel installation would be to install 4 panels as the previous calculation told, taking into account same tilt and losses conditions.

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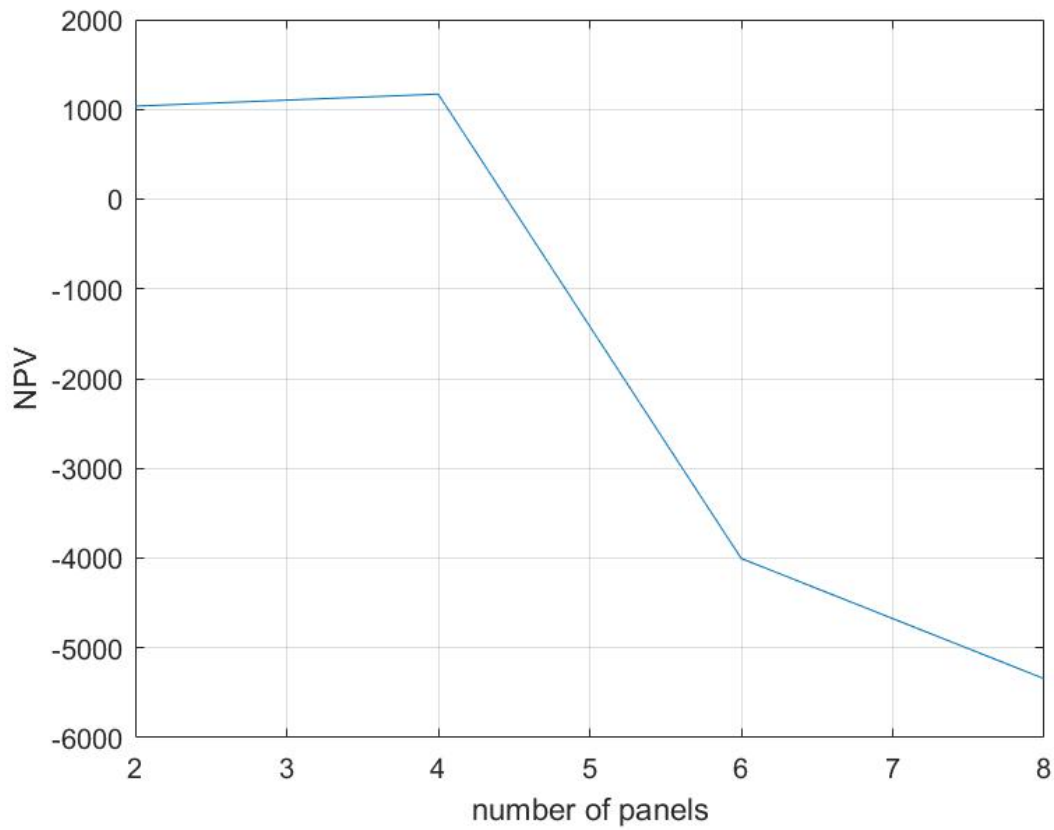
Figure 13 – NPV comparison between different number of panels

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CONCLUSIONS AND FUTURE PROJECTS

6. CONCLUSIONS AND FUTURE PROJECTS

The aim of the project is to reach a theoretical approach to the feasibility of a solar PV project. As it has already been tested, investments are retrieved within 10 years approximately.

Solar panels usually can produce energy for 30 years, if they are kept in a good shape, and maintenance requirements are done. This means, that the prosumer can consume energy freely for 20 years. Furthermore, he can even earn some money in those 20 years, by just considering low-price maintenance costs.

So, to sum up, the project shows that solar investments are currently a promising venture with low risk and high rewards, in terms of environmental protection and economic benefits. Low risk is supported by company guarantees that can be up to 25 years.

I found this project quite interesting, and I think that this theme can be highly exploited by making more research.

First of all, there shall exist more than a fixed model of consumption, that the user may use, based on the family members, routines, and the possibility to create a model for a household community sharing rooftop solar energy.

More input variables such as shadings, more irradiation precision according to the location or latitude orientation may create a better approach.

Also, a more complex brand analysis can be developed, just the main solar market brands where included. By taking guarantees and loans into account, the user may choose another option rather than the one which has a better quality-price ratio.

The fixed costs hypothesis may be substituted by a deeper analysis, where different inverters, installation costs, and companies may be chosen.

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CONCLUSIONS AND FUTURE PROJECTS

Finally, this project may be developed for every country in the world, considering the annual solar irradiation and the Feed-in-Tarif (Saving money or Earning money are the options depending on the existence of this variable), to choose the best way to benefit the prosumer.

In the Republic of Croatia it has been tested that the only way to make a profitable solar investment rather than for saving, is to install a lot of panels, with a very high first investment.

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APPENDIX: SUSTAINABLE DEVELOPMENT GOALS (SDG'S)

APPENDIX: SUSTAINABLE DEVELOPMENT GOALS

(SDG'S)

This project is very linked with the development of a more sustainable world. The whole goal of the project is to reduce pollution caused by non-renewable power plants (such as thermal, or nuclear plants).

The main SDG that can be found in the project is SDG 7, related to an Affordable and Clean Energy. Investing in solar photovoltaic power is one of the best options regarding the carbon footprint, everybody can actively participate in pollution issues by just buying some panels, a technology that is turning cheaper and cheaper. This project could ensure access to electricity to all citizens, even those who are off-grid, due to the fact that panels do not require a connection to the main grid.

The project is also related to SDG 13, Climate action. The Paris Agreement states that the Temperature rise must be below 2ºC, citizens installing panels is a variable that was not taken into account some years ago. Now, everybody knows that with some particular investment, that is beneficial for both Investor and world, this temperature limit can be achieved, and with great results. Also water residues and water temperature rise caused mostly by condensation in thermal plants, can be eliminated with photovoltaic energy, there wouldn't be any need to keep those power plants..

The final goal that can be found is SDG 11, building Sustainable cities and communities, and this one is really important if you take into account that by 2050, two thirds of humanity will be living in cities, and with conventional energy producing methods there wouldn't be enough for everybody. Solar panels for households open a window, to a responsible self-production, everybody would be more aware about what they consume, because they have to be aware about what they produce. In that sense resilient societies and economies could be achieved

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APPENDIX: SUSTAINABLE DEVELOPMENT GOALS (SDG'S)

Another important fact related to sustainable cities is that new business opportunities, and thus new employment opportunities are being created. This issue is very important, taking into account that the new COVID-19 crisis is increasing the unemployment rate.

Quantification of the impact of the contribution to the SDG:

- 70% of worlds emissions may be eliminated with photovoltaic technology
- Currently, 14.2% of the citizens have a lack of electricity in their houses, this quantity could be reduced, because the solar investment for citizens with a lack of a near grid, doesn't require a grid extension.
- 10.3M jobs related to renewable sources can be currently created in just one year.

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APPENDIX: CODE

APPENDIX: CODE

```
%% Important fixed dataH0=1350;

%Annual average solar radiation in Croatia(kW*h/m^2)

radiation_stc=1000; %standart conditions (W/m^2)

T_stc=25;

E_price=0.108 %(€/KWh)= 0.8kn/kWh (cost+levies)

P_limit=500000 %W  -> 500kW



NPV=[];

%The main excels provide us the following information

%BrandsTable: main points of each brand: Wp, Efficiency, Annual
degradation

%CoupleModel: energy consumption of an average family(kWh/hour)

%Irradiance:  Irradiation(KWh/m2/hour)  and  temperature(°C)  in
Croatia

%% Panel data

prompt1 = 'How many panels? \n';

n = input(prompt1);%number of panels

prompt2 = 'Which is the panel tilt angle?(0° facing the sun) \n';
```

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APPENDIX: CODE

```matlab
angle=input(prompt2); %after accounting for the solar zenith angle
of the sun z

prompt3 = 'System losses in %?(Invertor,Battery) \n';

System_losses=input(prompt3);




I0=625*n; %cost of invertor, cables, instalation, battery.(€)

brands=readtable('BrandsTable.xlsx');

Wp=brands.Wattage_W_;

Wp_average=mean(Wp);

PR=brands.PanelEficciency___;

CostPerWatt=brands.ApproxCostPerWatt_AUDRetailInclGST___W_;

CoeffT=brands.TemperatureCoefficient_Pmax_____C_;

Degradation=brands.WarrantedAnnualPerformanceDegradationYear2_25__
_year_;



%% Production(CapacityFactor) and consumption Data Monthly

C_total=readtable('CoupleModel.xlsx');

C_total.hour=(24*C_total.hour)+1;

Consumption_M=table();

monthsC=unique(C_total.month);
```

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APPENDIX: CODE

```
E_cons_month=splitapply(@sum ,C_total.sum_kWh_,C_total.month);

Consumption_M.month=monthsC;

Consumption_M.E_cons=E_cons_month;




P_total=readtable('Irradiance.xlsx');

P_total.hour=round(24*P_total.Hour)+1;

Production=table();

monthsP=unique(P_total.Month);

H0_hourly=P_total.GlobalHorizontalIrradiance_W_m2_;

P_total.TotalIrradiance=H0_hourly
*cos((angle*pi)/180)*0.001;%GHI=DHI+DNI*cos(z)

%globalhorizontalirr=directnormalirr*cosz+diffusehorizontalirr

maxIrradiance=splitapply(@max
,P_total.TotalIrradiance,P_total.Month);

meanIrradiance=splitapply(@mean
,P_total.TotalIrradiance,P_total.Month);

Production_M.month=monthsP;

Production_M.maxIrradiance=maxIrradiance;

Production_M.meanIrradiance=meanIrradiance;
```

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APPENDIX: CODE

```
H_prod_month=splitapply(@sum
,P_total.DirectIrradiance_kWh_m2_,C_total.month);

%% Production and consumption Hourly

Consumption_H=table();

hoursC=unique(C_total.hour);

E_cons_hour=splitapply(@mean ,C_total.sum_kWh_ ,C_total.hour);

Consumption_H.hour=hoursC;

Consumption_H.E_cons=E_cons_hour;

E_1day=sum(Consumption_H.E_cons);


Production_H=table();

hoursP=unique(P_total.hour);

maxIrradiance=splitapply(@max
,P_total.TotalIrradiance,P_total.hour);

meanIrradiance=splitapply(@mean
,P_total.TotalIrradiance,P_total.hour);

Production_H.hour=hoursP;

Production_H.maxIrradiance=maxIrradiance;

Production_H.meanIrradiance=meanIrradiance;

H_prod_hour=splitapply(@mean
,P_total.TotalIrradiance,C_total.hour);

H0avg=sum(H_prod_hour);
```

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APPENDIX: CODE

```matlab
figure;

plot(H_prod_hour);

title('Hourly Irradiance');

ylabel('Irradiance(kW/m2)'); xlabel('hours');

%Production calculus


brands.Area=Wp./(PR/100)/radiation_stc;

A=brands.Area;

A_mean=mean(A);

brands.cost=Wp.*CostPerWatt*n+I0;

H0=sum(P_total.TotalIrradiance);

brands.E_annual=H0*A.*(PR/100)*n*(1-(System_losses/100));%annual
solar output of the PV(kWh)(i);

E_annual=brands.E_annual;

costall=brands.cost;


X = categorical(brands.ProductName);

figure;

bar(X,brands.E_annual);

title('Annual production of each brand');

ylabel('Annual Energy Production(kWh)');
```

```matlab
figure;

bar(X,brands.cost);

title('Cost of each brand');

ylabel('Cost of n panels + I0 ($)');

        %% Economic Analysis Monthly

%individual analysis for each brand

bestNPV=-100000000;

TopBenefit=[];

for i=1:size(brands)

        %Here the annual production taking into account Temperature
and annual

        %degradation is calculated.


P_total.E_perhour_0=P_total.TotalIrradiance*A(i)*n*(PR(i)/100)*(1-
(System_losses/100));%annual solar output of the PV(kWh)(i);


P_total.E_perhour_T=P_total.E_perhour_0.*(CoeffT(i)/100).*(P_total
.Temperature__C_-T_stc);%Energy lowered by Temperature

    P_total.E_perhour=P_total.E_perhour_0+P_total.E_perhour_T;
%energy output each hour

    E_monthly=  splitapply(@sum  ,P_total.E_perhour,P_total.Month);
%energy output every month without degradation

    E_annual=sum(E_monthly);
```

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APPENDIX: CODE

```matlab
cost=costall(i);

Benefit=[];

Benefit(1)=-cost;

t=25; %(years)

k=0.04; %interest rate

exports=min(C_total.sum_kWh_-P_total.E_perhour,0);

imports=max(C_total.sum_kWh_-P_total.E_perhour,0);

totalexports=sum(exports);

totalimports=sum(imports);

Exchange.day=C_total.day;

Exchange.month=C_total.month;

Exchange.year=C_total.year;

Exchange.hour=C_total.hour;

Exchange.exports=exports;

Exchange.imports=imports;


Exports_month=splitapply(@sum,Exchange.exports,Exchange.month);


Imports_month=splitapply(@sum,Exchange.imports,Exchange.month);

%section means 1(household), 2(industry)

section=1;
```

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Appendix: Code

```matlab
if abs(totalexports)>abs(totalimports)

    section=2;

end

%to choose selling instead of saving(Feed-in-Tariff options for other
%countries), turn savings,expenses and E_cons_household to 0

if section==1

for j=1:t

        if j==1

            E_prod_household=E_monthly;

            E_cons_household=Consumption_M.E_cons;



            E_exc=(E_prod_household-E_cons_household);%energy excedente per month

            Incomes=0;

            Expenses=0;

            Savings=0;

            for y=1:size(E_exc)

                if E_exc>0

                    Incomes=Incomes + E_exc(y)*0.8*E_price;
```

```
                Savings=Savings+
E_cons_household(y)*E_price;

                    else

                        Expenses = Expenses - E_exc(y)*E_price;

                        Savings=Savings+
E_cons_household(y)*E_price;

                    end

            end

            Benefit(j+1)=Incomes+Savings-Expenses;


        else

            E_prod_household=E_monthly-
E_monthly*(Degradation(i)/100)*j;

            E_cons_household=Consumption_M.E_cons;



            E_exc=(E_prod_household-E_cons_household);%energy
excedente per month

            Incomes=0;

            Expenses=0;

            Savings=0;

            for y=1:size(E_exc)
```

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APPENDIX: CODE

```
                    if E_exc(y)>0

                        Incomes=Incomes + E_exc(y)*0.8*E_price;

                        Savings=Savings+
E_cons_household(y)*E_price;

                    else

                        Expenses = Expenses - E_exc(y)*E_price;

                        Savings=Savings+
E_cons_household(y)*E_price;

                    end

                end

                Benefit(j+1)=Incomes+Savings-Expenses;



        end

    NPV(i) = pvvar(Benefit, k);

    PP(i)= -Benefit(1)/Benefit(2);

    IRR(i)= irr( Benefit);



    end

    end

    if section==2
```

```
    for j=1:t

        if j==1

            E_prod_household=E_monthly;

            E_cons_household=Consumption_M.E_cons;




            E_exc=(E_prod_household-E_cons_household);%energy
excedente per month

            Incomes=0;

            Expenses=0;

            Savings=0;

            for y=1:size(E_exc)

                if abs(Exports_month)<abs(Imports_month)

                    Incomes=Incomes                          +
Exports_month(y)*0.9*(E_price/2);

                    Savings=Savings+               (E_monthly(y)-
abs(Exports_month(y)))*E_price;

                else

                    Incomes=Incomes                          +
Exports_month(y)*0.9*(E_price/2)*Imports_month(y)/abs(Exports_mont
h(y));

                    Savings=Savings+               (E_monthly(y)-
abs(Exports_month(y)))*E_price;
```

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APPENDIX: CODE

```matlab
            end

        end

        Benefit(j+1)=Incomes+Savings;


    else

        E_prod_household=E_monthly-
E_monthly*(Degradation(i)/100)*j;

        E_cons_household=Consumption_M.E_cons;



        E_exc=(E_prod_household-E_cons_household);%energy
excedente per month

        Incomes=0;

        Expenses=0;

        Savings=0;

        for y=1:size(E_exc)

            if abs(Exports_month)<abs(Imports_month)

                Incomes=Incomes                        +
Exports_month(y)*0.9*(E_price/2);

                Savings=Savings+              (E_monthly(y)-
abs(Exports_month(y)))*E_price;

            else
```

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APPENDIX: CODE

```
                    Incomes=Incomes                        +
Exports_month(y)*0.9*(E_price/2)*Imports_month(y)/abs(Exports_mont
h(y));

                    Savings=Savings+                (E_monthly(y)-
abs(Exports_month(y)))*E_price;

                end

            end

            Benefit(j+1)=Incomes+Savings;




        end

    NPV(i) = pvvar(Benefit, k);

    PP(i)= -Benefit(1)/Benefit(2);

    IRR(i)= irr( Benefit);



    end

    end

    if NPV(i)>bestNPV

            bestNPV=NPV(i);

            TopBenefit=Benefit;

        end

end
```

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APPENDIX: CODE

```
%% Choosing the best brand

brands.NPV=transpose(NPV);

brands.PP=transpose(PP); %payback period of each brand

brands.IRR=transpose(IRR);

[~,maxidx] = max(brands.NPV);

brands(maxidx,:)



%E_monthly=E_monthlyall(maxidx);

%E_hourly=E_hourlyall(maxidx);

cost=costall(maxidx);




E_prod_hourly=H_prod_hour*A(maxidx)*n*(PR(maxidx)/100)*(1-
(System_losses/100));



E_prod_day=E_prod_hourly;

E_cons_day=Consumption_H.E_cons;



figure;

plot(hoursP, E_prod_day);

hold on;
```

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APPENDIX: CODE

```matlab
plot(hoursP, E_cons_day);

title('Hourly Production and Consumption(MEAN)');

ylabel('Energy(kWh)'); xlabel('hours');



E_prod_household=H_prod_month*A(maxidx)*n*(PR(maxidx)/100)*(1-
(System_losses/100));

E_cons_household=Consumption_M.E_cons;

figure;

plot(monthsP, E_prod_household);

hold on;

plot(monthsC, E_cons_household);

title('Monthly Production and Consumption(SUM)');

ylabel('Energy(kWh)'); xlabel('months');

E_exc=(E_prod_household-E_cons_household);%energy    excedente    per
month

E_exc_annual=sum(E_exc);



Best_number=[];

h=1;

for p= n-2: n+2
```

```
P_total.E_perhour_0_best=P_total.TotalIrradiance*A(maxidx)*p*(PR(m
axidx)/100)*(1-(System_losses/100));%annual  solar  output  of  the
PV(kWh)(i);


P_total.E_perhour_T_best=P_total.E_perhour_0.*(CoeffT(maxidx)/100)
.*(P_total.Temperature__C_-T_stc);%Energy lowered by Temperature


P_total.E_perhour_best=P_total.E_perhour_0_best+P_total.E_perhour_
T_best; %energy output each hour

    E_monthly_best=                            splitapply(@sum
,P_total.E_perhour_best,P_total.Month); %energy output every month
without degradation

    E_annual_best=sum(E_monthly_best);

    E_cons_annual=sum(E_cons_month);

    Best_number(h)=E_annual_best-E_cons_annual;

    h=h+1;

end


X= n-2:n+2;

figure;

bar(X,Best_number);

title('Choosing the best number of panels');

ylabel('Energy(kWh)');
```

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APPENDIX: CODE

```
Benefitsum=cumsum(TopBenefit);

figure;

plot(Benefitsum);

ylabel('Benefit(€)'); xlabel('year');
```