# COMPARISON OF PV+THERMAL SYSTEMS AND PV/T SYSTEM IN TERMS OF TECHNO-ECONOMIC PERFORMANCE AT THE SAME ROOF AREA

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ABSTRACT

Solar energy is of great importance in an energy sources for different aspects. Electricity and thermal yields are possible from this infinite source. Although more traditional and old version of solar energy use is thermal collectors, nowadays photovoltaic systems are very popular for electricity generation from solar energy. Due to the demand of electricity increasing, consumers have started to generate electricity on their roofs. Thus, the roof area should be considered for both thermal and electricity. That is why PV/T, the applied jointly, becomes a new version of roof applications. In this article for the limited roof area, combination of PV and thermal application is compared with PV/T, based on techno-economic performance; and optimum rated area sharing for PV and thermal combination is determined.

## 1. INTRODUCTION

The more common version of solar based energy solution, which is thermal, already fulfilled the applied roof area. In addition, during the evolution of energy sources, when the demand of electricity increasing and grid infrastructure becomes micro-size, consumers have started to be called as “Prosumer” which means they become producers, as well. Thus, the limited area should be optimized for both thermal and electricity applications. It means that one restriction for PV, thermal and PV/T is the size of area especially roofs are separated for these combinations. However, getting more performance means efficiency. And efficiency can be supplied by using latest version of technologies. When efficiency increases, the price of installed system is also affected relatively and increases. These whole criteria affect the system techno-economical performance.

Needed thermal and electricity can be supplied simultaneously and close to each other, researches have been focused on supplying both thermal and electricity simultaneously at same size which is called PV/T systems. This solution also gives chance to benefit from same parameter, whose reaction is reverse for two systems, such as temperature. It is known that temperature has a negative effect on PV systems; on the other hand it has a positive impact on thermal ones. This research provides PV and thermal system simulation results for the consumers based on limited area. Furthermore, for the same size, helps to take the results of PV/T. It becomes easy to compare PV and thermal system combination and PV/T results. If the size stays same, the applied system considers providing as much as benefits with the optimized area sharing with PV and thermal combination. Moreover, for same circumstance profit from PV/T can be compared with this combination.

The consumer who needs both hot water and electricity can be domestic user. That is why, in examples, usually these types of consumers are used. And, the applied area assumed to be non-shaded with near objects (row, buildings, trees etc.).

The designed system is also taken into account with a natural tilt as 25°. South part of roof is considered and the size of the roof is determined as 100 $m^2$. The simulated design can be seen in the figure below. In addition, the roof’s long and short edges are not determined metrically; this provides flexibility for orientation of modules or collectors based on area.

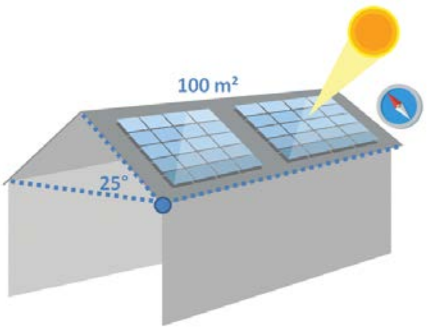

Fig. 1. The assumed roof area for system application

## 2. ELECTRICITY AND PV SYSTEM

First application is providing electricity from PV system at the roof area. The assumed roof area is given in figure 1. According to system design parameters which are given in the table 1; application properties and the steps for energy generation are given at the table 2.

Table 1. PV System design parameters

| Property | Value |
|---|---|
| Roof Area | 100 $m^2$ |
| Used Module Max Power ($P_{max}$) | 250 W |
| Module Size | 1 m * 1.6 m = 1.6 $m^2$ |
| Module Efficiency | 15.6% (Polycrystalline) (at std. test conditions) |
| Inappropriate Area | 20% (20 $m^2$) |
| Available Area | 80 $m^2$ |
| Wind Speed | 3 m/s |
| Reference Ambient Temperature | 25°C |
| Temperature Coefficient of PV | 0.32% |

The whole roof area cannot be used due to service roads, objects at roof etc. Thus, 80 $m^2$ is available area where 12,5 kW system can be applied thanks to formula below.

$$Installed\ Capacity = \frac{Roof\ Area}{Module\ Area} * P_{max} \quad (1)$$

This is the installed capacity of power, so the energy generation of the system can be calculated per year. For the solar system application, 1650 kWh/$m^2$ global horizontal irradiation (GHI) is assumed.

At the first step of yield analysis, the point for conversion of irradiation plays an effective role. Physical models are used for this transformation of the irradiation from horizontal to an oriented module version. This can be calculated directly by the software tools such as PVSYST [1]. It is equal to the ratio of the incident irradiation on the plane, to the horizontal irradiation. In other words, it means what you gain or loose when tilting the collector plane. The model of Hay and Perez are the transposition methods for PVSYST. Usually the model of Perez leads to higher results than the one of Hay. Since both procedures are established and validated, the arithmetic average of models can be considered. The designed system, transposition factor is defined as 111% with PVSYST for different places at Turkey with the tilt 25°. Thus, at the first step, GHI is converted to irradiation on module. Then this irradiation value is converted from metric to $kW_p$ based method. For the assumed system, standard polycrystalline PV modules are considered whose maximum power capacity is defined as 250 W/module. These 6x10 cells oriented standard module version, the area is approximately 1.6 $m^2$.

In PV system, the energy equation can be defined as below;

$$Q_{Solar} = \mathbb{P}_{el} + Q_{loss} \quad (2)$$

At that system each part of the system should be considered separately. Firstly, the electricity efficiency can be defined as below;

$$\eta_{el} = \frac{\mathbb{P}_{el}}{Q_{solar}} \quad (3)$$

which is equal to equation below;

$$\mathbb{P}_{el} = \eta_{el} * Q_{solar} \quad (4)$$

One of the components in the equation is defined for solar energy on PV module which is calculated by the equation below;

$$Q_{Solar} = G * A_{pv/t} \quad (5)$$

For the Eqn. (3), electrical efficiency can be calculated with the equation below [2];

$$\eta_{el} = \eta_{el,ref}[1 - \beta_{el} * (T_{cell} - T_{ref}) \quad (6)$$

For the equations above there is an unknown point, cell temperature, which should be calculated with a specific formula. According to Muzathik [3], cell temperature can be calculated with the equation;

$$T_{cell}(°C) = 0.943 * T_{ambient} + 0.0195 * Irradiance - 1.528 * Windspeed + 0.3529 \quad (7)$$

If the system parameters are entered at the equation above the cell temperature is found as 55°C. It is already defined that for roof of 80 $m^2$; 12,5 $kW_p$ can be applied. As a conclusion, from this system 20,663 kWh electricity is generated per year. From irradiation to electricity at the output of the module, the irradiation is exposed to different parameters which can be followed with the table below;

Table 2. Yield analysis of PV system per year

| Steps | Value |
|---|---|
| Global Horizontal Irradiation | 1,650 kWh/$m^2$ |
| Transposition Factor | 111% |
| Irradiation on Module | 1,831.5 kWh/$m^2$ |
| 1 kWp (4x250Wp) Area | 6.4 $m^2$ |
| Total Installed Capacity | 12,500 W (12.5 kW) |
| Irradiation on 1 kWp System | 11,722 kWh/kWp |
| Module Efficiency at given conditions | 14.1% |
| After Module Efficiency Applied | 1,652.8 kWh/kWp |
| Result for Whole Roof | 20,663 kWh |

The steps above are directly associated with the performance of the system. If the other environmental and component based effects are applied to the system, the result of PV system per $kW_p$ will be changed.

According to the electricity price in Turkey, for domestic users, it costs 0.4482 TL/kWh [4]. It means that without other environmental and asset effects, the total amount of energy can be bought approximately with 9,261 TL (2,437 $) per year. According to online platform related to gas and electricity [5], a standard family with parents and 2 children has consumed 253 kWh per month which is equal to 3,036 kWh per year. Thanks to system applied on roof, 6.8 standard families need is provided by generated electricity at the roof. However, for these types of system, if the exact number is not accessed the value is rounded at exact lower value which means maximum 6 families can be fed with this energy.

## 3. HOT WATER AND THERMAL SYSTEM

Solar energy is also used to provide hot water for consumers. That is why solar collectors also applied on roof area. This method is more traditional version for roof applications and widespread. Although there are different versions of collectors used for providing hot water, the main version is flat plate collectors. To make controlled experiment, whole parameters will stay same for same roof, except system aim is changed. Thus, system design parameters are defined as below.

Table 3. Thermal system design parameters

| Input | Value |
|---|---|
| Roof Area | 100 $m^2$ |
| Collector Size | 1 m * 2 m = 2 $m^2$ |
| Temperature of Output Water | 65°C |
| Temperature of Input Water | 15°C |
| Specific Heat Capacity of Water | 4.18 kJ/kg-K |
| Inappropriate Area | 20% (20 $m^2$) |
| Collector Efficiency | 73.7% |
| Available Area | 80 $m^2$ |

In the experiment the main aim is to use as much as possible roof area to apply solar collectors and getting hot water. The main issue is that units may vary but they can be standardized. According to the exemplified collector efficiency, hot water capacity is determined as 1,858,254 litres for whole 80 $m^2$ roof.

Table 4. Yield analysis of thermal system per year

| Step | Value |
|---|---|
| Global Horizontal Irradiation | 1650 kWh/$m^2$ |
| Transposition Factor | 111% |

Table 4. Yield analysis of thermal system per year (cont'd)

| Step | Value |
|---|---|
| 1 kWh | 860.42065 kcal |
| Irradiation on Collector (kcal) | 1,575,860 kcal/m$^2$ |
| Efficient Energy on Collector | 1,161,409 kcal/m$^2$ |
| For Whole Roof | 107,985 kWh<br>92,912,720 kcal |
| Hot Water Capacity | 1,858,254 litre |

During this calculation the significant equality is given below;

$$Q = \dot{m} * c * (T_{output} - T_{input}) \qquad (8)$$

At first, the capacity of roof is defined for hot water energy conversion, and then total amount is defined from equation. The significant point for considering is that fluid is water; therefore, kg and litre conversion can be done directly with same amount.

According to Turkish Statistical Institute data [6], daily consumption of water is 217 litres per person. With the same parameters as family, parents and two children, consumption of total water is 316,820 litres per year. Let's assume that half of it is hot which almost 158,410 litres. Thanks to roof top application of solar collectors, 11.7 families can be fed with this system in terms of hot water, thus 11 families are considered due to total provision. If the solar system is not applied, to heat the same amount of water, it is need to burn natural gas. Burning 1 m$^3$ natural gas can supply 10.64 kWh energy. Thus, to heat same amount of water it is needed to supply approximately 10,150 m$^3$ natural gas. The cost of 1 m$^3$ natural gas is charged with 1.22 TL, which is equal to 12,400 TL (3,263 $) approximately.

## 4. PV/T SYSTEM AND OUTPUTS

Hybrid energy system uses two or more energy sources in order to increase the overall efficiency. For example, photovoltaic systems use only the photons from electricity to generate an electricity and heat from solar irradiation which increase the temperature of photovoltaic cells and reduce its efficiency. Thanks to PV/T systems use not only electricity but also the thermal energy generated by solar irradiation, the extraction of energy via a heat transfer fluid at the same time for heating, also cool the photovoltaic panels and increase electricity generation. PV/T is a combination of solar collectors, which includes of a PV module for the electrical energy and solar collector for the high efficiency thermal energy, in the same area and frame. The visual demonstration of the PV/T module is seen below.

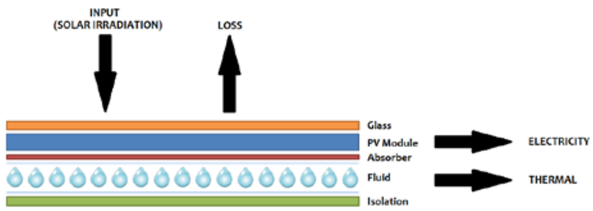


Fig. 2. PV/T Model

According to the figure above, PV/T system energy equation can be defined as below;

$$Q_{Solar} = \mathbb{P}_{th} + \mathbb{P}_{el} + Q_{loss} \qquad (9)$$

At that system each part of the system should be considered separately.

For the term of heat loss, it is important to find overall heat transfer coefficient. At the beginning, the comparison of PV and PV/T for this term should be done to find value of it for both cases. Heat loss can be calculated with the formula below;

$$Q_{loss} = U_L * A_{pv/t} * (T_{cell} - T_{amb}) \qquad (10)$$

For just PV application, overall heat transfer coefficient calculation is demonstrated with the figure below;

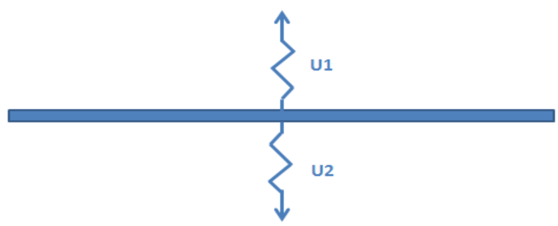


Fig. 3. Overall heat transfer coefficient demonstration for PV

It is seen that the total overall heat transfer coefficient equation becomes

$$U_L = U_1 + U_2 \quad (11)$$

Where;

$$U_1 = U_2 \quad (12)$$

Thus;

$$U_{1,2} = \frac{U_L}{2} \quad (13)$$

At that point, if all point stay same for PV, thanks to all others known parameters; total of upper and lower overall heat transfer coefficients is calculated as 52.44 W/m$^2$-K. However, for PV/T which is seen in the figure below. The heat loss occurs at the just upper side, since the lower side is integrated with thermal collector and the system benefit from the heat loss of lower side to generate thermal energy. The schematic description for heat loss at PV/T can be seen in following figure.

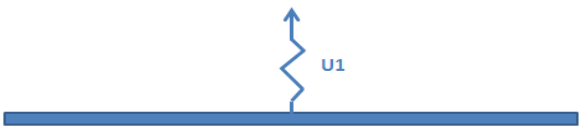


Fig. 4. Overall heat transfer coefficient demonstration for PV/T

Thus for PV/T, calculation for heat loss can be done with same formula by using half of overall heat transfer coefficient which is calculated for PV system.

$$Q_{loss} = U_{L\,(PV/T)} * A_{pv/t} * (T_{cell} - T_{amb}) \quad (14)$$

Where;

$$U_{L\,(PV/T)} = U_1 = \frac{U_L}{2} \quad (15)$$

Other effects are dismissed during the calculation of overall heat transfer coefficient. And for PV/T system it is determined as half of 52.44 W/m$^2$-K which is equal to 26.22 W/m$^2$-K. The other term of equation is electricity, whose efficiency is already defined in Eqn. (3) and Eqn. (4).

For whole energy analysis each terms should be re-calculated. If all parameters stay same, and thermal yield is preserved; there is one missing point, which is cell temperature of PV/T, is calculated as 32.74°C by using equation (9) where heat loss is calculated by using overall heat transfer coefficient for PV/T as given in equation (15). At that circumstance, new efficiency of the module is calculated as 15.2%. At that time, whole parameters at the general energy equation for PV/T is defined. Thanks to design parameter are given in the table below.

Table 5. PV/T system design parameters

| Input | Value |
|---|---|
| Roof Area | 100 m$^2$ |
| Collector Size | 1 m * 2 m = 2 m$^2$ |
| Temperature of Output Water | 65°C |
| Temperature of Input Water | 15°C |
| Inappropriate Area | 20% (20 m$^2$) |
| Available Area | 80 m$^2$ |
| Global Horizontal Irradiation: | 1650 kWh/m$^2$ |
| Transposition Factor: | 111% |
| Irradiation on Collector (kWh): | 1831.5 kWh/m$^2$ |
| PV Module Efficiency | 15.2% |
| Temperature Coefficient of PV Module | 0.32% |
| Ambient Temperature | 25°C |
| Wind speed | 3 m/s |

When the electricity yield by PV/T system is taken into account; it is calculated as 22,291 kWh. This also proves that PV/T electrical efficiency is higher than just PV due to heat transfer to working fluid which is flowing in thermal part of PV/T. At that situation, thermal yield was assumed same as just thermal case, which have been already calculated as 107,985 kWh.

Again, according to the electricity price in Turkey, for domestic users, it costs 0.4482 TL/kWh. It means that without other environmental and asset effects, the total amount of energy can be bought approximately with 9,991 TL (2,629 \$) per year which feeds 7.3 family whose rounded below version is 7 standard families. In that calculation, thermal yield was assumed same thus system still feed 11 standard families hot water and the earning was calculated as 12,400 TL (3,263 $) per year.

## 5. RESULTS AND CONCLUSION

Briefly; the three versions of application benefits are given in tables below;

Table 6. Number of families whose needs are provided with different system at same roof

| System | Fed Nr. Of Family |
|---|---|
| Thermal | 11 |
| PV | 6 |
| PV/T | 11 (In terms of hot water) + 7 (In term of electricity) |

In terms of economically the earnings can be sum up as below;

Table 7. Earning from different system combinations at same roof (1 $ = 3.8 TL)

| System | Earning per Year |
|---|---|
| Thermal | 3,263 $ |
| PV | 2,437 $ |
| PV/T | 5,892 $ |

With developing the method above, for same size area, changing combination applied area rate of PV and thermal gives the results below in terms of number of families with fed.

Table 8. Combination of PV and thermal system results

| PV Rate | Number of Families (For Electricity) | Thermal Rate | Number of Families (For Hot Water) |
|---|---|---|---|
| 0% | 0 | 100% | 11 |
| 10% | 0 | 90% | 10 |
| 20% | 1 | 80% | 9 |
| 30% | 2 | 70% | 8 |
| 40% | 2 | 60% | 7 |
| 50% | 3 | 50% | 5 |
| 60% | 4 | 40% | 4 |
| 70% | 4 | 30% | 3 |
| 80% | 5 | 20% | 2 |
| 90% | 6 | 10% | 1 |
| 100% | 6 | 0% | 0 |

In this study, the considered point is always in order to provide both electricity and thermal together. That is why the minimum number of family becomes a restriction. At that circumstance with using table 8 above it shows that 60% PV and 40% thermal application gives optimum result for 80 $m^2$ to provide maximum families' hot water and electricity needs together. On the other hand, PV/T application provides hot water for 11 families and electricity for 7 families which means 7 families' whole electricity and hot water needs are supplied with PV/T at the same size area. However, at 60% PV system and 40% thermal system case, the earning decreases to 2,933 $ (11,145 TL). This calculated earning is almost half of the earning when same 80 $m^2$ area is constructed with PV/T which is seen in the table 7.

If the same amount of families' electricity is provided, which is equal to 4 families, with the PV/T system; it is calculated that 6 families' hot water need is also provided. At that time, the necessary area for PV/T system reduced to almost 46 $m^2$, which is almost half of the used area at the combination of PV and thermal system.

To sum up, for optimum area sharing case, 4 families electricity and hot water can be supplied with combination of thermal and PV system; however, with PV/T system for 4 families hot water and electricity is totally supplied and 2 more families hot water consumption is also provided with using just 46 $m^2$ roof area. In that case earning per year becomes 3,405 $ (12,939 TL), which is 15% more than the earning of PV and thermal system combination case for 4 families which needs 80 $m^2$ roof area.

As a result; for specific needs and limited area circumstance, it is better to use PV/T instead of PV and thermal system combination to decrease need of area and increase the earning. Furthermore, construction becomes easier thanks to the decreasing unit installations.

## Nomenclature

$P_{max}$ Maximum power at STC (Watt)
$Q_{Solar}$ Total solar energy (kWh)
$Q_{loss}$ Heat loss (kWh)
$T_{amb}$ Ambient temperature (°C)
$T_{cell}$ Cell temperature (°C)

$U$ Overall Heat Transfer Coefficient ($W/m^2$-K)
$A_{pv/t}$ Area of PV/T ($m^2$)
$\mathbb{P}_{el}$ Electrical energy (kWh)
$\mathbb{P}_{th}$ Thermal energy (kWh)
c Specific heat capacity (kJ / kg-K)
$\dot{m}$ Mass flow rate (kg/s)

**Greek Letters**
$\eta_{el}$ Electrical efficiency

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