APPLICATION OF A NOVEL SOLAR PV TRI-GENERATION HEAT PUMPING FACADE IN A HIGH PERFORMANCE BUILDING IN ANKARA

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Abstract: A solar PVTC (Solar Photo-Voltaic, Thermal, and Cooling) module was designed in order to achieve a cumulative *COP* value greater than one for the utilization of solar energy in combined power, heat, and cold generation. The integrated facade comprises PV arrays, heat distributing plates, and thermo-electric cooling (TEC) elements, all sandwiched together. Part of the electric power generated drives the TEC modules. The heat distributing plate between the solar PV and the TEC module transfers heat in a useful manner from them simultaneously and delivers to the building for various domestic uses. Thus the heat absorbed by the solar PV, which reduces its thermal efficiency is transformed into useful heat in the building. Simulation and early prototype tests have shown that the thermal efficiency of the new tested PVTC system is 0.89, exergy efficiency is 0.48, and the cumulative solar heat pumping *COP* is 1.25. Carbon emissions reduction potential is also favorable: about five times higher than a simple solar PV module under identical conditions.

Key Words: Solar Facade Heat Pump, High Performance Building, Radiant Panel

1 INTRODUCTION

The benefits of using radiant panel heating and cooling system in high performance buildings depend on the exergy of the energy source. A radiant panel system, which is a low-exergy system, must be coupled with low-exergy energy resources like low-intensity renewable energy sources or waste heat or cold. This brings the possibility of using co-generation systems and ties their waste heat. Part of the power generated may also be tied to a ground-source heat pump. When the objective is to reduce carbon emissions especially for net-zero energy buildings, usually solar and wind energy resources are prioritized. For example, solar collectors are used for space heating with radiant panel systems. In fact, both make a good coupling due to the fact that moderate temperatures make a good match with moderate water temperature requirement of radiant panel systems. This match also reduces carbon emissions, because such a good temperature match also reveals itself in exergy match. According to the Rational Exergy Management Model (REMM), the compound carbon emission per hour is given in Equation 1. Here, c_b is the carbon equivalency of the energy source and η is the first-law efficiency of the system. The subscript "p" stands for the power plant that the building is

attached via the grid, with an overall power delivery efficiency of η_T. The term U_b stands for the overall heat transfer coefficient of the building envelope (W/K).

$$\sum CO_2 = \left[\frac{c_b}{\eta_b} + \frac{c_p}{\eta_p \eta_T}\left(1-\psi_R\right)\right] \times \left[U_b\left(t_a - t_o\right)\right] \quad (1)$$

The second term in Equation 1 represents avoidable carbon emissions due to exergy imbalances. The term ψ_R is the REMM efficiency, which is defined in Equation 2 (Kilkis, S. 2009). Equation 3 is the demand exergy for unit load and Equation 4 is the supply exergy based on the supply temperature T_f of the energy source in kelvin. T_{ref} is the reference temperature.

$$\psi_R = \frac{\varepsilon_{dem}}{\varepsilon_{\sup}} \quad (2)$$

$$\varepsilon_{dem} = \left(1 - \frac{T_{ref}}{T_a}\right) \quad (3)$$

$$\varepsilon_{\sup} = \left(1 - \frac{T_{ref}}{T_f}\right) \quad (4)$$

2 DEVELOPMENT OF A NEW COP PARAMETER

Radiant panel heating technology is recently coupled in many countries with PVT (Solar photovoltaic and heat). Radiant panel cooling is now possible PVTC (Solar Photovoltaic, thermal, and cooling) systems that is presented herein. Speaking about PVT, a new rating parameter, which is not available yet, was developed in this study in order to accurately quantify benefits of coupling PVT and PVTC technology with radiant panel heating and cooling concept. This new rating parameter combines environmental benefits and fuel savings benefits. To begin with the development of the new parameter, *PES* equation of the EU Directive [1] on co-generation may be adopted to form a trial form of PES_{PVT} solution:

$$PES_{PVT} = \left[1 - \frac{1}{\frac{CHPH\eta}{CHPHref} + \frac{CHPE\eta}{CHPEref}}\right] = \left[1 - \frac{1}{\frac{0.55}{0.85} + \frac{0.17}{0.35}}\right] = 0.117\,(11.7\%) \quad (5)$$

The reference values *CHPEref* and *CHPHref* are given in the same Directive. Because the solar PVT is on-site, the reference efficiency values must be selected accordingly (on-site availability

of energy and power). The overall electric power generation, distribution, and transmission efficiency is about 0.35. In a typical PVT system, solar- thermal efficiency is about 0.55 and solar-power efficiency is typically 0.17. The condensing-boiler reference efficiency is about 85% on average load. Yet, the result obtained by the above trial form of PES_{PVT} equation and the moderate fuel savings percentage does not represent actual benefits of a PVT system. This is primarily because it does not factor in the rational exergy management efficiency, namely Ψ_R, which is a strong metric about environmental benefits of alternative energy systems. A recent study has modified Equation 5 in terms of Ψ_R. The result is PES_{RPVT} [2]:

$$PES_{RPVT} = \left[1 - \frac{1}{\left(\frac{CHPH\eta}{CHPHref} + \frac{CHPE\eta}{CHPEref}\right) \times \frac{(2-\psi_{Rref})}{(2-\psi_{RPVT})}}\right] = \left[1 - \frac{1}{\left(\frac{0.55}{0.85} + \frac{0.17}{0.35}\right) \times \frac{(2-0.2024)}{(2-0.34)}}\right] = 0.18\,(18\%) \quad (6)$$

Here, Ψ_{RPVT} for PVT is approximately equal to 0.34. The reference value, namely Ψ_{Rref} is 0.2024 [3]. The result is not successful again and in fact, meaningless, because what it tells us is that one may save only 18% of fossil fuel "used." In a solar PV or PVT system, no fossil fuel use is involved unless a fossil fuel-hybrid system is employed. Above two tries to factor in benefits of radiant panel systems to PVT and PVTC systems are not successful. This condition justifies the need for a new rating parameter for alternative energy-combined heat and power systems. The new parameter is a simple modification of Equation 6. Then actual fuel savings of a solar heat-pumping PVT system, which supplies all power and heat demand (Q_A/Q =1) is:

$$COP_{RA} = PES_{RPVT} + \left(\frac{Q_A}{Q}\right)\left(1 - PES_{RPVT}\right) = 1\,(100\%) \quad (7)$$

Here, Q_A is the sum of all heat (and or cold) supplied by a solar and or any other alternative energy resource. Q is the total heat and power demand of the building. If for example, in a hybrid (Boiler and grid power integrated solar PVT) system Q_A/Q is 0.45, then Equation 7 gives a fuel savings ratio of 0.4775 (47.75%) for the same example. In a further refinement of Equation 7 exergy difference between heat and power is recognized:

$$COP_{RA} = PES_{RPVT} + \left(\frac{Q_{AH}\varepsilon_{AH} + Q_{AE}}{Q_H\varepsilon_{HH} + Q_E}\right)\left(1 - PES_{RPVT}\right) \quad (8)$$

In Equation 8, Q terms are broken down into heat and power components and into their respective exergy values, namely ε_{AH}, ε_{AE}, ε_{HH}, ε_{EE}. Exergy of electric power, namely ε_{AE} and ε_{EE} were taken unity. Compare a PVT system with a condensing-type "wall-mounted combi" heater used on-site (in the building) in summer for domestic hot water supply, where the electric power is supplied from the national grid. PES_{Rcombi} value in this case is negative even the condensing boiler may have a peak on-site thermal efficiency of 0.95. This is primarily because; it does not

generate power at all. Actually a “high-efficiency” boiler wastes fuel rather than saving it [4, 5]. Therefore, the overall energy savings of a PVT system compared to natural-gas condensing boiler is 108%.

$$PES_{Rcombi} = \left[1 - \frac{1}{\left(\frac{CHPH\eta}{CHPHref} + \frac{CHPE\eta}{CHPEref}\right) \times \frac{(2-\psi_{Rref})}{(2-\psi_{RPVT})}}\right] = \left[1 - \frac{1}{\left(\frac{0.95}{0.95} + \frac{0}{0.35}\right) \times \frac{(2-0.2024)}{(2-0.06)}}\right] = -0.08\,(\text{-}8\%)$$

3 BUILDING PVTCI ON THE FACADE

In spite of their environmental benefits, the problem with PVT is the fact that there is not much thermal load during summer season. Instead cooling loads are dominant. Therefore, in order to avoid wasting solar heat from PVT panels, it needs to be utilized for generating cold downstream the process, like by an absorption unit or by a metal-hydride system. Although these are technically feasible, the system mechanics becomes quite complicated and operation and installation costs may be uneconomical. In this study an electronic version of the concept has been developed. The system comprises an integrated, sandwiched unit that employs the electro-thermal effect both for heating and cooling: IBPVTCI (Building Integrated Photo-voltaic, thermal, and cooling) system. The heat generation is multiplied by the absorbed heat from the building while electronically cooling the building using thermo-electric cooling (TEC) modules. Because comfort cooling is performed mainly to satisfy solar gains of a building in summer, the new PVTCI heat output is even more than the solar radiation on the PVTCI.

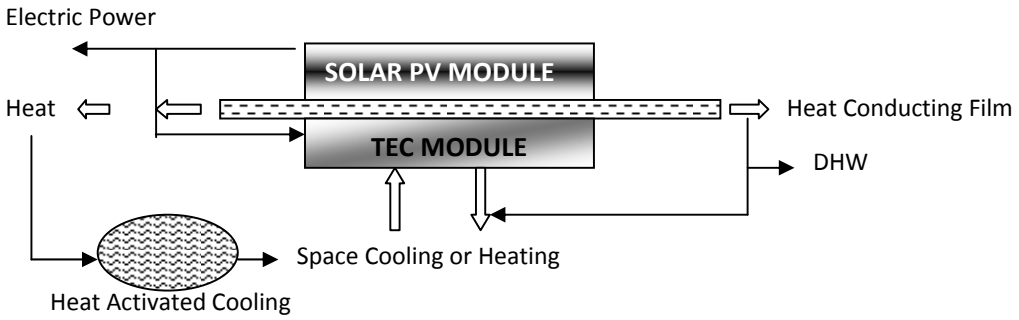


Figure 1: The Basic Concept of the PVTCI System [6].

The same sheet thermally insulates both modules, because this commercially-available sheet is practically a perfect insulator along its thickness direction. This conductive sheet performs in such a manner that while the heat is transferred to a proper heat sink at the demand point, it cools the PV module and maintains the proper temperature difference across the TEC module. During a typical operation, the solar PV module generates electric power at its optimum performance level, because it is cooled. With a simple control, this solar power may be optimally split between the power need of the building and the power need of the TEC module. When the TEC module is exposed directly or indirectly (by a second thermally conducting sheet layer to the indoor space), it electronically heats or cools the indoor space primarily by thermal radiation

and secondarily by natural convection through its exposed surface, depending upon the polarity of the dc power supplied by the PV module, which is controllable. In the cooling mode, TEC module absorbs heat from the indoor space and transmits it to the same heat conducting sheet between the TEC module and the PV module. Thus this system multiplies the heat gain that may be usefully utilized in the same indoor space or other building zones. If the cooling load is the dominant load, part of this heat may be further utilized in a heat activated cooling system like a metal-hydride system. In space heating, power polarity change makes the TEC module a radiant heating module. In this case, the heat conducting film brings the PV heat indoors.

4 DESIGN OF THE PVTCI SYSTEM

The concept was engineered in an optimized manner and a prototype was manufactured with an emphasis of the possibility of using this concept on building facades, which may receive solar energy as a building element with an optimized inclination. This modular system may be cast into non-load bearing bricks while it also acts like an insulating material. This introduces a fourth useful function to the concept, namely thermal **insulation** of the building envelope (PVTC**I**). Figure 4 shows the wall application schematics. This additional thermal insulation reduces thermal loads of the building and results in a better energy and exergy balance and match between PVTCI outputs and building demands. According to this figure, the heat exchanging medium is the heat conducting sheet that may be connected to a hydronic circuit at the end of the walls; one supply and one return circuit that transfers the absorbed heat to demand points or to other heat activated cooling systems. The inclination angle, α from the vertical and rotation angle, β from the normal to the facade is optimized for minimum shading of adjacent modules and maximum solar gain. Internal gaps thus formed are filled with conventional insulating material. This application also satisfies sound and vibration insulation.

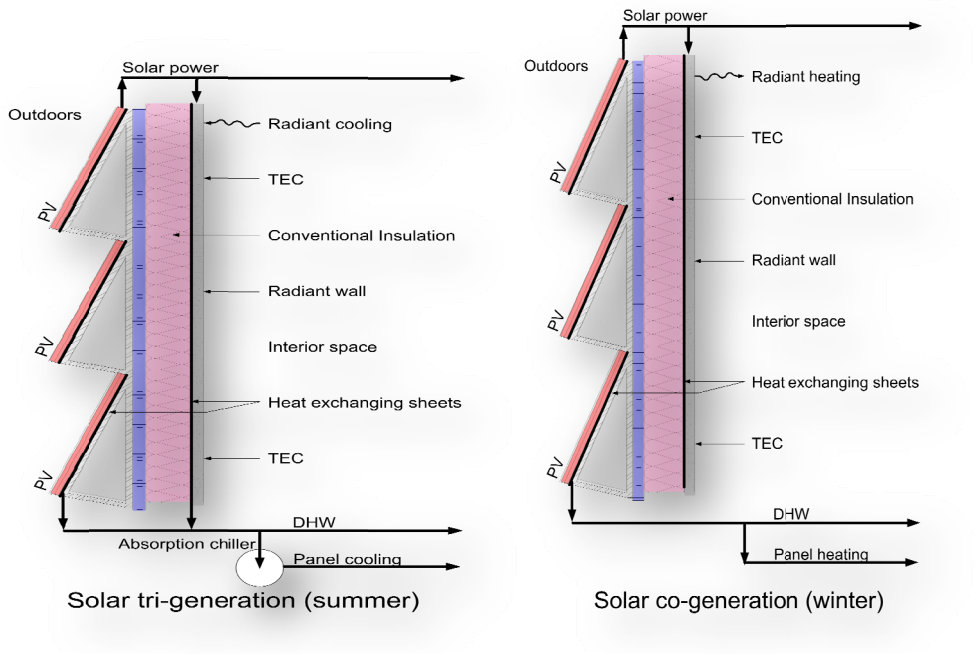


Figure 2: Building integrated version of PVTCI, Summer and Winter Mode [7].

5 PROTOTYPE DEVELOPMENT

A prototype solar PVTC heat pumping system was developed and manufactured [8] for testing the performance of a unit panel. The basic design, of a single PVTCI module is shown in Figure 5. Here, the conducting sheet is thermally riveted to a metal plate at one end. The metal plate is connected to a hydronic copper pipe, in which water circulates to transfer the heat from the module to points of use and thermally sinks both PV and TEC modules. The calculated performance of the PVTCI system under ideal conditions with optimally sized and selected PV and TEC modules is summarized in Figure 6. In this calculation, the cooling *COP* of TEC is 0.70, PV efficiency is 0.2 [9]. Typically, the solar power s equally split between the building and TEC modules. For an incident total solar insolation on a 1 m^2 of PVTCI panel surface area of 160 W, the breakdown of the useful outputs is given below.

- Total solar electric power supply = 32W.
- 16W to electric demand (Net power supply to the building)
- 16W to TEC (For internal use in PVTCI modules)

- TEC cooling capacity = 11.2W at an indoor DB air temperature of T_a = 295K (22°C)
- Solar heat capacity = 115.2W at T_{heat} = 343K (70°C).
- Total useful output: 115.2W + 16W + 11.2W + Heat gain from comfort cooling

The first-law efficiency of the module under ideal conditions is; 142.4W/160W = 89%, excluding the heat gain from indoors during comfort cooling.

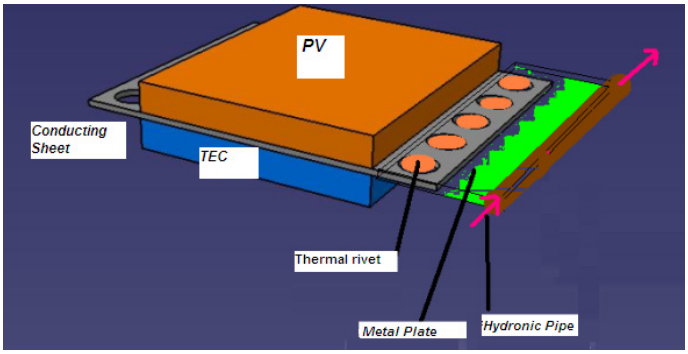


Figure 3: A Single Solar Tri-generation (PVTCI) module [8].

6 COOLING SURFACE ENHANCEMENT

A thermal pinch exists between the solar PVTCI system and its radiant surface exposed to the indoor space to be electronically heated or cooled. This pinch occurs on the TEC surface: TEC surface area, namely A_{TEC} is not sufficient to transfer heat between indoors and the TEC surface and eventually in the PVTCI module. The total heat transfer (Natural convection and radiation) between a vertical radiant panel (TEC) surface and the indoors, namely Q_{TEC} at given thermal conditions is calculated by Equation 9 [10]. In this equation, *AUST* is the area-average temperature of unconditioned indoor surfaces. This equation is valid for both sensible heating (Negative Q_{TEC}) and cooling (Positive Q_{TEC}). PVTCI module may also heat indoors during winter by a simple polarity switch of the dc power supply and disengaging the heat sink. The coefficient

1.78 and the power 1.32 may slightly change according to the angle of inclination and spacing of the PVTCI modules. The heat transfer coefficient regarding natural convection may develop into the forced-convection regime at the presence of another installed HVAC system. For typical surface dimensions of a single TEC module (0.05 m x 0.05 m), Q_{TEC} is about 0.18W if t_p is 18°C, *AUST* is 28°C and t_a is 24°C. But the same TEC module is capable of absorbing 5W of heat in the cooling mode under the same operating conditions. Then, the surface area required under natural convection and thermal radiation conditions must be enhanced. The only feasible solution is to increase A_{TEC}. In order to achieve this, a new surface enhancement technique was developed as shown in Figure 6. In addition, natural convection coefficient increases due to its enhanced nucleation. The conical fins give the maximum augmentation ratio. In order to further increase the surface area and radiant angle factors, the plane of the fin base is a semi-spherical surface on which the cones follow a volute pattern that is subject to Equation 9 [10].

$$Q_{TEC} = A_{TEC}\left[1.78\left(t_a - t_p\right)^{1.32} + 5\times10^{-8}\left\{\left(AUST + 273.15\right)^4 - \left(t_p + 273.15\right)^4\right\}\right] \quad (9)$$

The first-law efficiency does not recognize the different exergy values of the PVTCI module outputs and their exergy balance with the indoor space loads. In order to make a better analysis of the module, Rational Exergy Management Model (*REMM)* was used for the exergy analysis [2, 11]. Using REMM, first, solar energy was mapped in terms of an equivalent source temperature, T_{solar}. In Equation 10, P_{si} is the peak solar insolation on-site, which in Figure 7 P_{si} is 800 W/m^2, T_{sun} is 5800 K. T_g is the reference environment temperature (283K) based on average ground temperature site. Equation 11 yields T_{solar} to be 683K.

$$\frac{P_{si}}{1367\mathrm{W/m^2}} = \frac{\left(1-\frac{283\mathrm{K}}{T_{solar}}\right)}{\left(1-\frac{283K}{T_{Sun}}\right)} \quad (10)$$

$$\varepsilon_{\sup} = \varepsilon_{solar} = \left(1-\frac{T_g}{T_{solar}}\right)\times P_i = \left(1-\frac{283}{683}\right)\times 160W = 93.7W. \quad (11)$$

On the demand side of the PVTCI system, if heat is supplied at 343K (70°C):

$$\varepsilon_{heat} = \left(1-\frac{T_g}{T_{heat}}\right)\times P_{heat} = \left(1-\frac{283}{343}\right)\times 115.2W = 20.1W \quad (12)$$

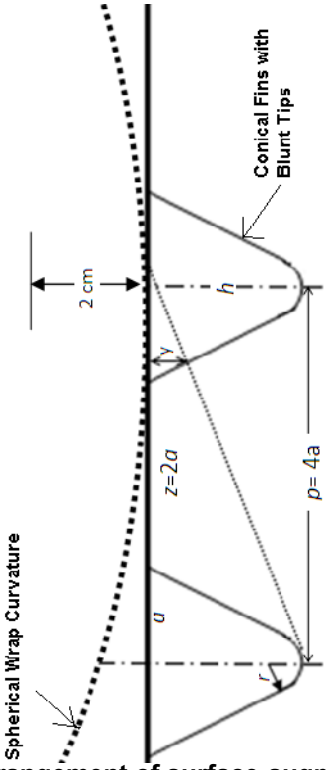


Figure 4: Arrangement of surface-augmenting [11].

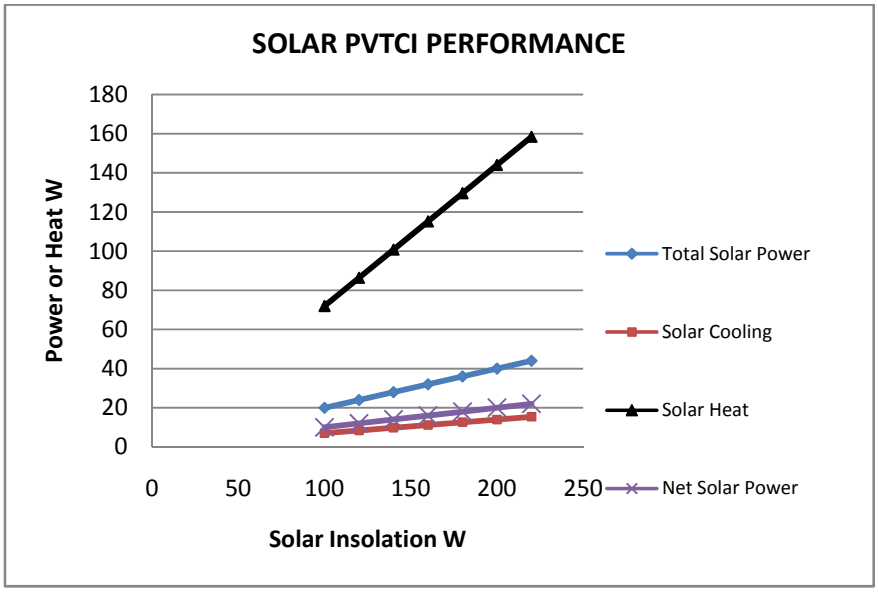


Figure 5: Performance Data for the PVTCI system [12].

$\varepsilon_{electric}$ = 16W {Net output to the building}

$$\varepsilon_{cooling} = \left(1 - \frac{T_g}{T_{solar}}\right) \times P_{cold} = \left(1 - \frac{283}{683}\right) \times 11.2W = 6.6W \quad (13)$$

The total exergy output, ε_{dem} on the demand side of the PVTCI module is the sum of 20.1 W, 16W, 6.6W and 2.7W due to the heat reclaimed from the cooled indoor space. The sum is 45.4W. Then the rational exergy management efficiency, Ψ_R of the PVTCI module is:

$$\Psi_R = \Sigma\varepsilon_{dem}/\varepsilon_{sup} = 45.4W/93.7W = 0.48. \quad (14)$$

If Equation 14 is applied to the PV case, which delivers 32W electric only ψ_R is;

$$\Psi_R = 32W/93.7W = 0.34 \quad (15)$$

and the first-law efficiency is 0.20 (32W/160W). Table 1 summarizes the benefits of PV, PVT, and PVTCI in comparison to condensing boiler system in a building connected to the national power grid. According to Table 1, η of the PVT system is 0.92 ([32+115.2]/160). If only part of the heat produced like 25% is used in DHW supply, η and Ψ_R values may reduce down to 0.38 and 0.40, respectively. Yet, a more important problem of the PVT system is that, supply of plain heat does not respond to space cooling. A PVTCI system just does that by better matching HVAC loads.

Table 1: Performance Comparison of PV, PVT, and PVTCI with the Base Scenario.

PARAMETER	SOLAR APPLICATION SCENARIOS			BASE SCENARIO
	PV	**PVT**	**PVTCI**	**Boiler and grid**
First-law Efficiency, η	0.20 (max.)	0.92	0.89; *COP*=1	Boiler:0.95 ;
REMM Efficiency, Ψ_R	0.34	0.55	0.48	0.06
Fossil Fuel Savings, PES_{RA}	100%	100%	100%	-8%
COP	<<1	<1	≥1	-
Relative CO_2 reduction potential $\eta/(1-\Psi_R)$	0.3units	0.63 units	1.6 units	-1 unit
Service(s)	Power only	Power and heat	Power, heat, cold	Heat only
Typical pay-back period*	12-14 years	8 years	5-6 years	never

*Depends on many factors. These values are only for relative evaluation of scenarios and the base case.

7 SHOWCASE

Building a high performance, green headquarters building of the ESER Contracting and Industry Co. Inc. in Ankara was completed in 2010. Figure 6 shows the existing facade of this building with conventional PV modules. Now, this facade is going to be replaced by PVTCI system. The optimum green mechanical system comprises a multitude of renewable and sustainable

mechanical components like wind turbines, solar PV, solar collectors, ground source heat pump, energy storage systems, and a natural gas driven trigeneration unit with absorption chiller unit. The combined heat and power unit (CHP) follows the electric power load of the building and also drives the ground source heat pump and the absorption chiller. It's useful heat output is mainly utilized in comfort heating. Thermal energy storage (TES) tanks are used, namely ice, cold, and hot water tanks. These store energy during off-peak thermal load periods by utilizing thermal energy from the CHP unit, absorption chiller output, its waste heat, and the ground-source heat pump. All these systems were sized such that they operate at almost constant peak capacity round the clock for the highest efficiency and the pay-back period is the shortest. Conventional condensing peaking and back-up boilers and centrifugal chiller systems complement the green mechanical system of the building. Ground-source heat pump that is driven by the CHP unit delivers comfort heating and cooling. Chillers top off the cooling capacity by storing cold in the ice storage tank. In order to decrease the building's power consumption, pumps and fans are all frequency controlled. This building also includes rainwater harvesting and grey water recycling systems. The goal of this green mechanical system, which is a hybrid composition of several systems, is to achieve minimum exergy destruction and life cycle cost goals along with the highest efficiency- a candidate for LEED gold. New façade system shall deliver heat, cold, and power.



Figure 6: ESER Building in Ankara and the PV Façade.

8 DISCUSSION AND CONCLUSIONS

In order to investigate and better rate the fundamental benefits of radiant panel heating and cooling, a new exergy analysis methodology was developed. This methodology can be parametrically applied to several combinations of low-exergy energy resources ad low-exergy building and may be used to optimize the exergy balance for minimum carbon emissions as depicted in Table 1. The solar PVTCI system has important implications in reducing carbon emissions in the building stock. The carbon emissions mitigation potential of a simple PV module and a PVTCI module per unit load, when REMM model is incorporated may be deduced in Equation 16 [5, 13]. According to Equation 16, a PVTCI module has the potential of replacing five times more carbon emissions from the stock. This study reveals that it is quite important to

consider both first and second-law of thermodynamics, especially in the REMM format in order to direct and guide future solar PV and TEC applications.

$$\frac{CO_{2\,PV}}{CO_{2\,PVCT}} = \frac{\frac{1}{\eta_{PV}}\left(1-\psi_{RPV}\right)}{\frac{1}{\eta_{PVTCI}}\left(1-\psi_{RPVCTI}\right)} = \frac{\frac{1}{0.2}\left(1-0.34\right)}{\frac{1}{0.89}\left(1-0.48\right)} = 5.6 \qquad (16)$$

According to Table 1, a PVTCI module has a REMM efficiency that is six times more than the base scenario. This means that the exergy of solar energy is better matched with low-exergy demand of a building equipped with radiant panels. REMM efficiency however is less than that of PVT. But PVTCI is simultaneously providing (more) heat and comfort cooling rather than only heat. The better service of PVTCI is reflected to its overall *COP*, which is higher. Figure 7 shows how the layers of the PVTC concept may be used in different combinations for optimum demand satisfaction. For example, PHVT case is a case where the TEC module cools the PV and maintains it at rated photo-electric efficiency. While doing that, it generates additional power while its cold side delivers useful heat at low temperatures like pre-heating the domestic hot water supply.

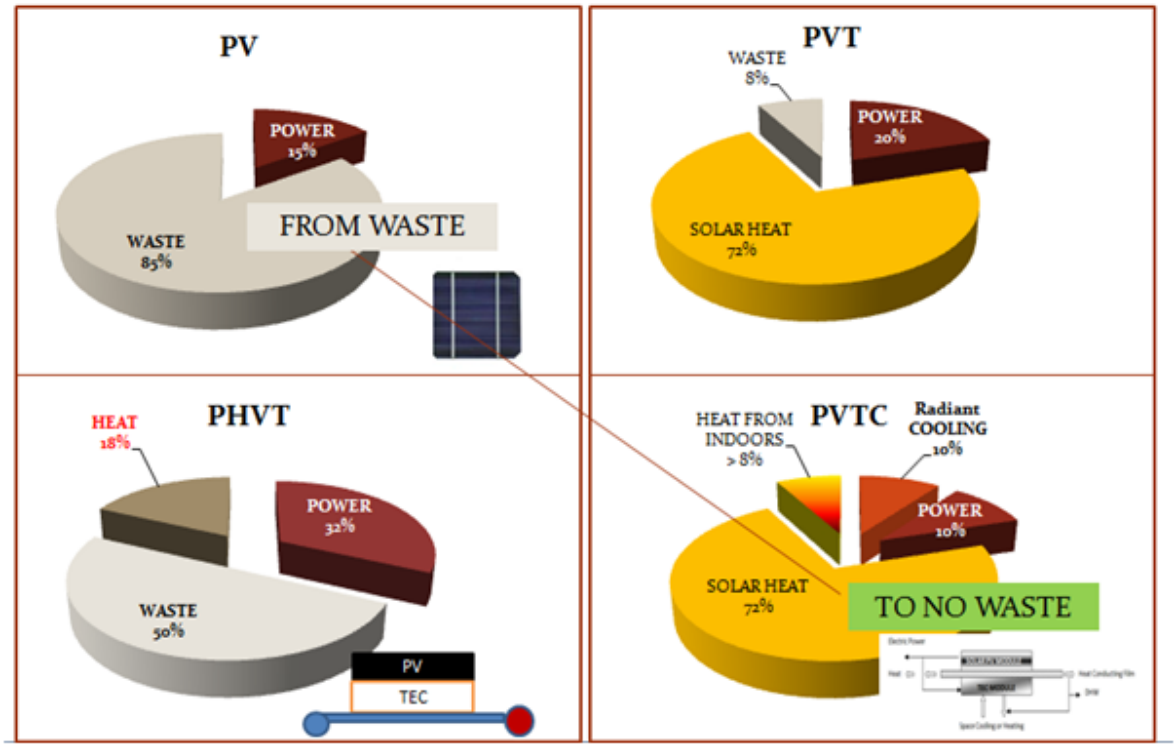


Figure 7: Different Combinations of PVTC Layers, [14, 15].

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