THE FIRST GRID-CONNECTED SOLAR BP GAS STATION IN GREECE

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ABSTRACT: BP of Greece has opened the first solar gas station in the country that covers part of its energy demand by photovoltaics. It is one of the first PV systems to be connected to the national electricity grid. The energy flows of the gas station have been monitored and the data were analyzed in order to study the contribution of the photovoltaic system in terms of avoided energy costs. The performance of the PV system is also presented and the utility connection issues are discussed. According to the results, the appropriate level of support measures for the introduction of PV systems in gas stations and other grid-connected applications may be proposed by BP in such a way, that the benefits exceed the financial risk. BP of Greece in cooperation with BP Solar is planning to replicate this application in other gas stations in Greece.
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1. PHYSICAL AND TECHNICAL PRESENTATION

The PV system was installed in October 1997 and is operational since then. It is composed of 54 BP Solar panels (BP-585L), of 85 Wp nominal power each, the total DC peak power being 4.6 kW. The PV array is composed of 6 strings of 9 modules, each one connected to one of six SMA grid tied inverters. The inverters being used are model SW 850 (850 W_{AC} nominal), single phase ($220V_{AC}$/50Hz), connected in pairs to each one of the 3 phases of the main electric board of the gas station. The modules are supported by a metal structure, arranged in rows on the roof of the mini-market store of the gas station, inclined at 50°, facing south (see Photo 1). In Figure 1, you notice a simplified electric diagram of the grid-connected PV system installed at the BP gas station.

Photo 1: A view of the solar BP gas station in Greece.

1. PV SYSTEM COST

The PV system is composed of the PV modules, inverters, cables, electrical board, switches, safety equipment, monitoring system and installation. Altogether costing approximately 53.5 KECU (1 ECU = 315 Dra). The metallic support structure for the PV modules on the mini-market store of the gas station was subcontracted separately, costing 18.5 KECU. The PV system, the monitoring system and the installation cost are considered high, as it was one of the first times such a system was installed in Greece. On the other hand, a close inspection of the metallic support structure reveals that it is over-designed for the application. The cost is considered unacceptably high and clearly it can be re-designed to be less expensive.

Strings of PV modules
1 2 3 4 5 6

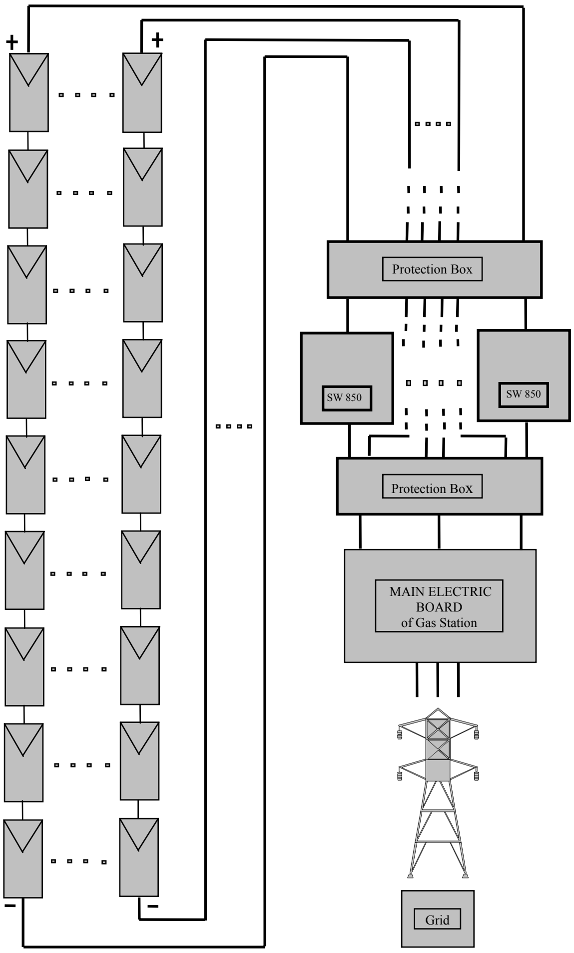

Figure 1: Simplified Electric Diagram of the

Grid-Connected PV System

2. UTILITY CONNECTION ISSUES

Law 2244/94 and the associated presidential decree [1] provide the framework for RES electricity production in Greece. The PV grid-connected systems of power less than 20 kWp are not required by the law to receive an installation license, although a license of operation is obligatory. The process starts with the request for connection to the Public Power Corporation (PPC) grid. PPC is looking into the application and decides about the suitability and safety of the system. The electricity plant must meet guideline #129 of PPC for grid connection of Autoproducers (those who generate electricity to cover for their own consumption and sell only their surplus energy, if any, to PPC) [1]. PPC's guideline is concerned with the measurement of power and safety measures (phase asymmetry issues, operation limits of voltage and frequency). The recorded values by PPC are :

- The incoming energy from PPC in kWh
- The incoming reactive energy from PPC in kVAh
- The outgoing energy to PPC in kWh

The Autoproducer receives two electricity bills, one for the energy consumed and one for the energy he has sold to PPC [2].

Electricity producing plants up to 100 kW, are allowed to connect to the Low Voltage grid. Plants with power greater than 100 kW are connected to the Medium Voltage grid through a transformer. The positive decision of PPC and the associated contract of connection to the grid submitted to the Ministry of Development in order to receive the license of operation. The whole process may take a few months.

3. ENERGY FLOWS / PERFORMANCE PRESENTATION

A data acquisition system has been installed that measures power and hence energy produced by the PV system, as well as power and the total energy consumption of the gas station. The daily energy balance of the gas station was examined and conclusions were drawn about the appropriateness of the size, performance and viability of the system.

Table I : Energy consumption bills of the gas station in Dra.

Consumption Period	**Monthly Consumption in kWh**	**Max. Power Demand (in kW)**	**Cost of Energy and Power with VAT included**
10/11/97 - 9/12/97	5,948	22	196,491
9/12/97 - 12/1/98	8,078	29.8	266,502
12/1/98 - 9/2/98	5,849	25.7	195,888
9/2/98 - 10/3/98	5,814	22.3	192,603
10/3/98 - 8/4/98	6,101	23.6	202,198
8/4/98 - 12/5/98	5,070	24.9	171,622
12/5/98 - 10/6/98	5,006	22.6	168,171
Total Energy Consumption in 7 Months	41,866	**Total Cost with VAT**	1,393,475

In Table I, the energy consumption of the gas station, the maximum power demand, and the total cost per month, are presented as they are established by the PPC bills.
The irradiance values of Athens at a surface inclined at 45° [3] were used for the estimation of the electric energy produced by the PV system over a year.

Table II : Assumptions for the annual electricity production calculations.

Annual Electricity Production Calculation Assumptions	
PV modules	
Power at STC (compared to mftr. data)	90 %
Power temperature coefficient	- 0.4 % / °K
Mismatch of modules	1 %
Wiring losses	1 %
Dust and dirt degradation	2 %
DC/AC Inverter	
Mean annual efficiency	85%

The monthly electricity production calculation in Table III takes into account the assumptions detailed in Table II with respect to the efficiency of operation of PV modules, PV cell operating temperature, average annual inverter efficiency, etc.

Table III : Monthly PV system electricity production and values used for monthly electricity calculation.

Month	Monthly Average Solar Irradiance at 45°, kWh/m2	Mean Monthly Tempe-rature in °C	Mean Monthly PV Cell Operating Temp. in °C	Mean Monthly Instanta-neous AC Power in kW, (4.6 kWp)	Total Monthly Energy in kWh, at 45°
Jan	95	10.5	35.5	3.24	307.45
Feb	104	11.6	36.6	3.22	335.03
Mar	128	12.9	37.9	3.20	410.10
Apr	144	17.1	42.1	3.15	453.19
May	162	21.9	46.9	3.08	499.33
Jun	163	26.6	51.6	3.02	492.06
Jul	179	29.3	54.3	2.98	533.83
Aug	188	29.2	54.2	2.98	560.93
Sep	167	25.3	50.3	3.04	507.07
Oct	142	20.0	45	3.11	441.33
Nov	115	16.3	41.3	3.16	363.17
Dec	94	12.5	37.5	3.21	301.68
Total in				Annual	

kWh/m^2	1,681			Total in kWh	5,205.19

Therefore, the estimated mean annual electric energy production of the 4.6 kWp DC PV system, inclined at 45° with respect to the horizontal plane with unobstructed air circulation at the back of the modules, is approximately 5,200 kWh. An important issue is the air circulation behind the PV module laminates. As they have been installed, the backs of the PV modules are covered with metallic panels impeding air circulation, that leads to higher PV cell operating temperature and a corresponding reduction of energy production. An increase of the working PV cell temperature by 10° Celsius decreases the average annual production by 4.4%.
Going back to Table I, one may extrapolate the average annual consumption of the gas station to be approximately 72,000 kWh (average monthly energy consumption of 6,000 kWh). Therefore, the installed PV system provides an annual energy penetration ratio of approximately 7.2%.

3.1 Analysis of energy flows
After resolving some problems with the data acquisition system during the first months of operation, we have analyzed the data for several days of the last few months. The daily collected data were in binary format, and subsequently were converted into ASCII format for further processing by a program created in LABView.

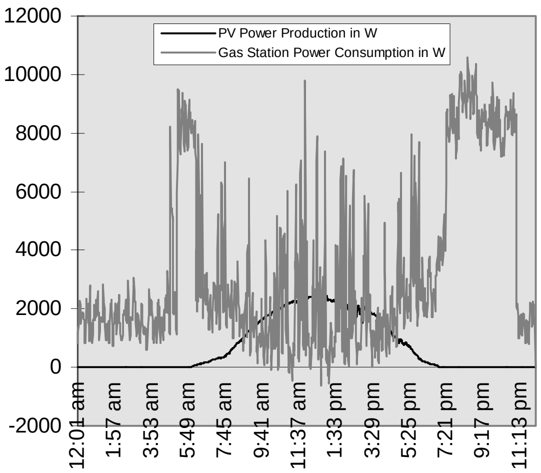

Figure 2 : Profiles of power consumption and power production on May 1st 1998.

Figure 2 presents the profile of the power consumed at the gas station and the power produced by the PV system on May 1st 1998. The power consumed during that day was 80.33 kWh and the energy produced by the PV system was 17.37 kWh. Therefore, the ratio of PV energy produced to the energy consumed by the gas station was 0.216. The power consumption profile of the gas station indicates that the higher power demand occurs during the hours that the lights are on, early in the morning and late in the afternoon.

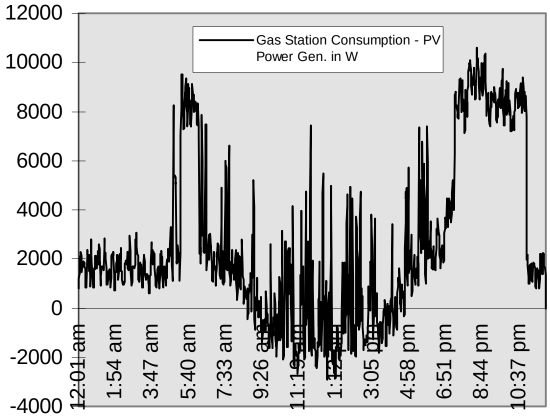

Figure 3 : Gas station power consumption minus the power produced by the PV system.

This pattern remains the same all year round, obviously with longer high power demand periods, early in the morning and in the afternoon, for the winter months. If the power production is subtracted from the power consumption of the gas station, see Figure 3, it is noticed that a significant amount of energy is transferred to the PPC grid during daytime hours. For May 1st 1998, it was calculated to be 5.57 kWh.

4. AVOIDED ENERGY COSTS

Table IV presents the payback rates for renewable energy producers in Greece as amended in August 1997.

TABLE IV : Payback Tariffs of electricity produced from RES (effective Aug. 1st 1997)

			Auto Producers Payback 70% of KWh selling price, in Drachma	**Indepen-dent Producers** Payback 90% of KWh selling price, in Drachma
Autonomous Island Grids	Energy (all Voltages)		18.08	23.25
Interconnected system	Low Voltage 220/380V	Energy	18.08	---
	Med Voltage 6.6, 15, 20, 22 KV	Energy	14.62	18.79
		Capacity	---	483 X σ* (50% of selling tariff)

* σ assumes the following values:
0.5 for wind and solar units
0.7 for small hydro units
0.9 for geothermal and biomass units

The gas station PV system is classified as an Autoproducer and the payback rate per kWh is 18.08 Dra. In this case, because the payback rate is lower than the charging kWh by the PPC (25.83 Dra/kWh) it is favorable to have coincidence of energy production by the PV system and local consumption. This way, a certain amount of energy is not charged by PPC and consequently the profit for the producer is higher, since each kWh not buyed from PPC saves the gas station 100% of the PPC charging price. For that reason, it is proposed to install PV systems that do not produce more power than the average demanded one during daytime hours, in order to maximize the profits. This is a viable initial approach with the photovoltaic technology, since its modularity permits system expansion at a later time, when the economic parameters change for the better for RES producers.
Table V presents economic data per DC kWp of installed PV system. As the cost for first time applications of PV systems is higher than the market prices, in the calculations of Table V market values of regular PV grid-connected systems are assumed. The grid-connected PV system cost per DC kWp is assumed to be 2.2 Million Dra (or 6.6 kECU) installed, the average lending rate over 20 years is taken to be 7%. The PPC electricity tariff increases yearly according to the inflation. Columns # 4,5,6 present the annual installment of capital and interest one would pay to a bank if he would have taken a loan with a 20 year floating rate as in column #2, a 10 and 20 year loan at a fixed rate of 7%.

Table V : Economic analysis per DC kWp of PV system.

				Lending Interest (%):	7		
				PV System Cost per kWp in Dra :	2200000		
				Lifetime of PV System in Years :	25		
				Initial Investment Cost in Dra :	1320000		
				Lending time in Years	20		
				Subsidy :	40		
				Yearly Production per DC kWp:	1200	AC kWh (Athens area)	
Year	Develop. of Lending Interest	Develo-pment of Inflation	20 Years Floating rate	10 Years Fixed 7% rate	20 Years Fixed 7% rate	Tariff Γ22 with VAT (18% Cost of kWh	Avoided Energy Cost with VAT (Dra
1997	12	6	124598.7	187938.3	124598.7	30.5	36575.3
1998	10	5	161842.7	187938.3	124598.7	32.0	38404.0
1999	9	4	151598.4	187938.3	124598.7	33.3	39940.2
2000	8	3	141992.1	187938.3	124598.7	34.3	41138.4
2001	7	3	133044.5	187938.3	124598.7	35.3	42372.6
2002	7	3	133044.5	187938.3	124598.7	36.4	43643.7
2003	7	3	133044.5	187938.3	124598.7	37.5	44953.1
2004	7	3	133044.5	187938.3	124598.7	38.6	46301.6
2005	7	3	133044.5	187938.3	124598.7	39.7	47690.7
2006	7	3	133044.5	187938.3	124598.7	40.9	49121.4
2007	7	3	133044.5		124598.7	42.2	50595.1
2008	7	3	133044.5		124598.7	43.4	52112.9
2009	7	3	133044.5		124598.7	44.7	53676.3
2010	7	3	133044.5		124598.7	46.1	55286.6
2011	7	3	133044.5		124598.7	47.5	56945.2
2012	7	3	133044.5		124598.7	48.9	58653.5
2013	7	3	133044.5		124598.7	50.3	60413.1
2014	7	3	133044.5		124598.7	51.9	62225.5
2015	6	3	131203.2		124598.7	53.4	64092.3
2016	6	3	131203.2		124598.7	55.0	66015.1
2017	6	2				56.1	67335.4
2018	6	2				57.2	68682.1
2019	6	2				58.4	70055.7
2020	6	2				59.5	71456.8
2021	6	2				60.7	72886.0
			2705061	**1879383**	**2491973**	In 25 Years :	**1360572.7**

The last column of Table V presents the annual avoided electricity cost due to local consumption of the PV system produced energy. The sum of avoided energy costs in 25 years cover the initial investment cost, when subsidized by 40%. Nevertheless, the situation is dynamic and in a few years the cost of PV systems without subsidy may be less than 3 kECU per DC kWp, while the liberalization of the energy production market in Europe and the possible carbon tax on conventional fuels may change significantly the assumed values in Table IV.

5. BP EFFORTS

In the framework of worldwide activities of BP, to develop alternative sources of energy, it has established a daughter company BP Solar that is involved in related studies, manufacturing and distributing of PV modules and systems. BP of Greece in cooperation with BP Solar has recently decided to develop a pilot PV plant in gas stations in order to study the possibility to cover part of their energy demand. This way, BP hopes to contribute in the effort for a cleaner environment. The appropriate level of support measures for the introduction of PV systems in gas stations have to be determined by BP in conformity with the results of this study. The offer to the gas station operators have to be such that the benefits of the PV systems exceed the financial risk and cost over a time period shorter than the lifetime of the system.

6. CONCLUSIONS

The general assessment for the photovoltaic system is positive, as it operates according to its specifications. This application has demonstrated the problems and possibilities of implementing grid-connected PV systems in Greece. BP of Greece in cooperation with BP Solar is planning to promote and replicate this application in other gas stations in Greece.

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