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Battery powered electric vehicles developed for light agricultural duties in remote areas in the southern Mediterranean region

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SYNOPSIS

Hilly and remote areas in the Southern Mediterranean region suffer a high cost of diesel fuel, problematic supply, poor or non-existent grid connections and lack of maintenance technicians to service farm grid generation systems and machinery. A prototype battery powered electric vehicle using a solar photovoltaic array (10 kWp) was installed at a monastery situated at Achkout (Lebanon) with a total agricultural area of 50 hectares, 10 hectares of which was under viticulture. The monastery and associated farmland previously relied on a diesel powered generator (35 kVA) and a diesel fuelled tractor (20 kW) for meeting electrical loads and motive power. This prototype battery powered electric vehicle or Renewable Energy Agricultural Multipurpose System (RAMseS) for Farmers has been developed under the European Union's FP6 programme to investigate the potential for the cleaner production of power, hence reducing the use of diesel fuels in agriculture. Data collected from the test site is presented. An economic analysis determined that if the current trends in inflation in the EU continue and fuel costs increase by 10% per annum, then the original RAMseS system will be economically viable. A further analysis looking at the adoption of new lithium titanate batteries reveals that these systems would be cost effective if these new batteries can be produced at a similar cost to lead acid batteries. Adoption of the RAMseS system for a 10 hectare vineyard would result in annual fuel and carbon dioxide saving of 4000 litres and 2.9 tonnes respectively. The use of alternative non-lead based batteries would save the use of nearly 21 tonnes of lead over the system's lifetime.

INTRODUCTION

Fossil fuel combustion has been linked to a number of serious global and local environmental problems alongside concerns over security and longevity of supply. Within the European Union (EU) the European Strategic Energy Technology Plan (SET-Plan, 2009) [1] has reported that 80% of primary European energy supplies are currently derived from the combustion of non-renewable fossil fuels. The combustion of fossil fuels generates carbon dioxide and other greenhouse gases (GHG), increasing their atmospheric concentration. Global levels of GHGs (measured in terms of carbon dioxide equivalent or CO_2e) reached 430 ppm in 2005 (a 64% rise since 1750) and are currently rising at a rate of 2–3 ppm per year (IPCC, 2007 [2] and Hofman *et al.*, 2009 [3]). It is predicted that this anthropogenic GH, increased due to mankind's use of fossil fuels, will raise mean global surface temperatures by 1.8°C to 6.4°C by the end of the 21st century (IPCC, 2007 [2]). Consequently, mean sea level is predicted to rise due to thermal expansion alone by 0.18 m to 0.59 m, relative to that during

1980–1999, by the end of 21st century. Past economic growth and prosperity in the developed nations has been built on the extensive use of fossil fuels which leaves them vulnerable to energy supply disruptions from other external sovereign regimes exporting energy, fluctuating energy costs and severe environmental change via anthropogenic climate change. In 2006 the EU imported 53.8% of its fuel usage, requiring 370.1 million tonnes of oil per annum for transport, which represented 38.7% of final energy demand [4]). For developing and newly industrialising countries, access to cheap and plentiful energy for transportation is a must, if economic development is to be achieved. Thus, the issue of replacing fossil fuel based energy systems is of concern due to economic (rising energy costs), environmental implications (anthropogenic climate change and other forms of pollution) and security of supply (unequal distribution of energy resources).

The SET plan [1] outlined the comprehensive policy framework that the EU has put in place to address climate and energy targets for 2020. A low-carbon economy is proposed aiming for an 80% reduction in carbon emissions, compared to 1990 levels, through the introduction of new renewable energy technologies and technology transfer. One method of reducing GHG emissions is the introduction of Battery Electric Powered Vehicles (BEPVs) to replace conventional Internal Combustion Engine Vehicles (ICEVs) as a source of motive power and to promote energy efficiency ([5], [6], [7] and Werber *et al.*, 2009 [8]), reducing carbon emissions from transport and providing an alternative fuel source to replace the finite fossil fuel supplies. Within the EU, transportation was responsible for the emission of 992.3 million tonnes of carbon dioxide in 2006 (EU Energy and transport figures, 2009 [4]).

Previous studies have found that the most appropriate application of renewable energy systems is for remote areas where diesel fuel is expensive, supply problematic and the local grid unreliable or nonexistent [6], [9]. This paper focuses on the application of a decentralised renewable energy system for supplying motive power in agricultural systems, as an area where a cost effective sustainable energy solution may be realised.

The RAMseS project supported under the EU's FP6 programme has investigated the potential of a Renewable Energy Agricultural Multipurpose System, for Farmers (RAMseS) in the Southern Mediterranean region, based on solar Photovoltaic (PV) arrays, as a means of reducing the use of fossil fuels for motive power in agriculture. Currently, agricultural vehicles are mainly powered using diesel fuel (typical energy content, 38.7 MJ l^{-1} [10], the combustion of which is associated with a number of environmental, economic and political problems. These remote agricultural sites offer the most likely locations where electric vehicles can be utilised cost-effectively, as well as providing environmental benefits. Therefore, a remote location for the RAMseS system was chosen for an initial assessment of electric vehicles for light agricultural duties. Remote Area Power Systems (RAPS) such as RAMseS are typically used as stand-alone or hybrid systems, in conjunction with diesel generators, to provide the power required for agricultural activities. Any additional electrical energy generated is stored in batteries to be used as required for motive or other agricultural electrical loads, thus reducing the operating time or requirement for diesel generators for generation of electrical energy [11]. In this case, the vehicle acts as part of the battery storage system, improving the performance of the solar PV array as well as providing motive power.

Various energy sources for powering agricultural vehicles were investigated by [5] reporting that diesel fuelled ICEVs can convert 23% of the energy contained within diesel fuel, whereas the conversion efficiency of BEPVs was 85%. It was estimated that BEPVs could undertake around 40% of the transport and motive duties on farms currently achieved using ICEVs [5].

The conversion efficiency of transforming stored potential energy in batteries and fuel tanks was compared by Fischer *et al.* [7]. As ICEVs have much higher losses in converting the chemical energy contained in fossil fuels into mechanical energy at the wheels it was found that the "crossover range" (below which electric powered vehicles have a higher energy density than gasoline powered systems) was 190 km (120 miles) for BEPVs using lithium ion batteries.

Shaahid and Elhadidy (2008) [12] undertook an economic analysis of hybrid PV-diesel-battery systems for supplying power for residential loads in hot regions. It was reported that simulations showed that a hybrid 4 kWp PV array with a 10 kW diesel generation system utilising 3 hours of battery storage could supply 22% of the electrical load. The cost of generating electricity by such a system was reported as $0.179/kWh when the cost of diesel fuel was $0.1/litre.

Mousazadeh *et al.*, 2009[a] [13] estimated the complete lifecycle emissions of the RAMseS BEPV comparing these to an ICEV tractor using SimaPro software, reporting that adoption of the RAMseS system would avoid the emission of 23 tonnes of CO_2 per annum, but the lead acid batteries used would result in the emission of 20.5 tonnes of lead during the vehicle lifetime.

Mousazadeh *et al.*, 2009[b] [14] reported that BEPVs for agriculture can convert 75% of the potential chemical energy within batteries to mechanical energy available at the wheels whereas the equivalent value for a Diesel ICEV (tractor) was 15%. This study considered a BEPV powered using a solar Photovoltaic (PV) array and lead acid battery storage. This system would be cost-effective compared with ICEVs for diesel costs greater than 1.8 €/litre.

Shaahid and El-Amin, 2009 [15] performed a techno-economic evaluation of off-grid hybrid photovoltaic-diesel-battery powered systems for the purpose of sustainable rural electrification in Saudi Arabia. The results found that a hybrid system comprising a 2.5 MWp PV array, a 4.5 MW diesel generator (three 1.5 MW units) and 1 hour of battery storage could supply 27% of the electrical load, reducing carbon emissions by 24% compared to a diesel only system. With a diesel fuel cost of \$0.1/kWh the cost of generating electricity was reported as \$0.170/kWh.

Werber *et al.* 2009 [8] compared the life cycle costs of an electric car to a similar gasoline ICEV investigating different costs of gasoline and driving ranges. The costs incurred for the ICEV was broken down into three categories, original vehicle cost, maintenance (only scheduled tasks not repairs) and fuel (gasoline) costs. Costs for BEPVs were categorised as original vehicle cost, maintenance, fuel (electrical energy) and batteries, as a function of desired range. All future cost were discounted to Net Present Value (NPV) using Equation (1) where c is the cost, d is the discount rate and n is the number of years from the initial purchase. This life cycle assessment assumed a 12 year vehicle life span, that electricity was provided from conventional electric power plant at a cost of \$0.104/kWh, and that the cost of gasoline increased linearly.

$$NPV = \frac{c}{(1 + d)^n} \quad (1)$$

It was reported that at a battery cost of \$500/kWh, BEPV's can be produced for similar lifecycle costs as ICEVs, if the range of the vehicle is 139 km, assuming the cost of diesel remained constant at 3 \$/gal over the 12 year lifespan. The disadvantages of ICEVs compared to BEPVs were listed as: inability of home refuelling, increased maintenance due to engine oil changes etc, increased levels of repairs due to higher ICEV complexity and emission of air pollutants during operation. However this study did not consider using renewable energy as the original energy source.

The work in this paper differs from these previous studies in that:

(1) Actual data collected from monitoring the solar PV system located at the RAMseS test site at Achkout is used to validate a RETscreen model detailing the monthly power generation and usage.
(2) The economic life cycle analysis in this work was undertaken using an experimentally validated model and discount and inflation rates based on current actual European economic trends over the last 10 years.
(3) An agricultural energy audit of the monthly mechanical power requirements for viticulture and olive tree cultivation is detailed. This is unique in that previous agricultural studies reviewing fuel/mechanical power requirements have only focused on annual values. Whilst annual figures may be sufficient for dispatchable fossil fuel based systems, for those relying on transient non-dispatchable seasonal energy sources and energy loads such as solar radiation and agricultural activities monthly information is vital if optimised PV system sizing and hence more cost effective installations are to be achieved. Over-sizing results in expensive wasted power generation in summer.
(4) The technical review of the RAMseS vehicle is based on tests carried out by the Institute for Building, Mechanization and Electrification of Agriculture (IBMER) based in Poznan, Poland. The design specifications of the RAMseS MST and the actual performance figures are presented.
(5) The technological, economic, geographical and political scenarios under which BEPVs supplied by solar PV arrays are economically feasible are examined to determine the likely impact of such vehicles in the Mediterranean region (where sufficient data were available).

An initial study was undertaken using a small farm in Lebanon as a test site for an installed PV array which was used to provide power for an electric vehicle for light agricultural duties. Figure 1 depicts the average annual global solar radiation levels [16] for the capital city of all the countries bordering the Mediterranean Sea.

From Figure 1, the level of solar radiation varies from 4.4 kWh m^{-2} day^{-1} in Spain (Madrid) to 5.9 kWh m^{-2} day^{-1} in Israel (Jerusalem). The Southern Mediterranean region is subject to a high level of incident solar radiation and thus well-suited for solar PV system applications. At many remote locations suitable for PV RAPs such as that powering the RAMseS BPEV within the southern Mediterranean region, traditional agricultural practices still abound. Thus a review of these practices and their typical energy demands is essential to gain the understanding required to design optimally-sized solar PV powered RAPS. The evolution of traditional agriculture within the southern Mediterranean region has been driven by the generic climatic conditions experienced and the typical topography of this region, [17].

1. The hot summer with low or zero levels of precipitation. Unless crops can be irrigated they must be either sown in autumn and

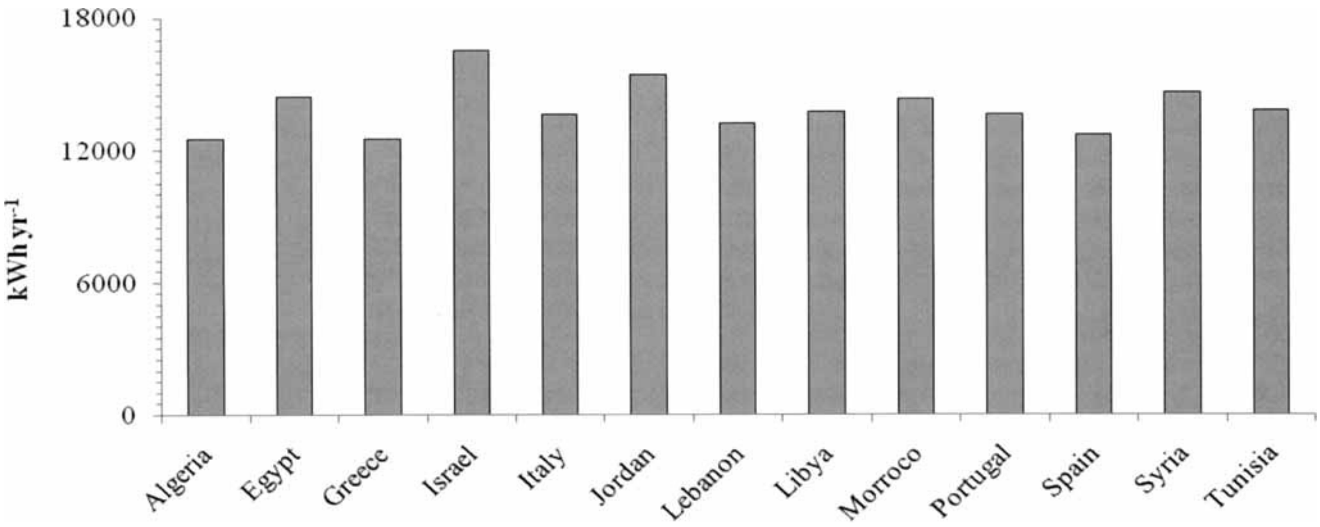

Figure 1 Global solar radiation experienced in Mediterranean countries adapted from, [16].

harvested in the early part of the summer or be drought-resistant varieties.

2. The mild wet winters and hot summers allow a wide range of crops to be grown i.e. during the winter period temperate crops can be produced, during the hot summer period, assuming adequate irrigation, sub-tropical crops can be grown.
3. Terrain: Typically agriculture is focused around land adjacent to the Mediterranean Sea itself. The generic topography of the region consists of coastal plains and low hills. Mountainous areas have more precipitation in winter and also some in summer.
4. The region surrounding the Mediterranean Sea typically experiences winters that are mild in temperature and high in precipitation, during the summer months the temperatures are hot and the level of precipitation is low.

THE RAMseS PROJECT

An agricultural site situated at a Monastery in Achkout (Lebanon) with total agricultural area of 50 hectares, 10 hectares of which was vineyards under cultivation was chosen as an initial test site. This site, typical of traditional Lebanese agriculture, is located 35 km North East from Beirut at 1000 m above sea level and mean solar irradiance is 4.5 kWh m^{-2} day^{-1} [16]. The total area of the farm is 50 hectares, 10 hectares devoted to viticulture and the other 40 used for grazing livestock. Before the installation of the solar PV array the Monastery relied on a diesel-powered generator (32 kW, maximum efficiency 35%) a diesel-fuelled tractor (20 kW, efficiency 23%) [18] an intermittent grid connection and had no electrical storage facility. At this location, the cost of diesel fuel is high due to transport costs; supply is problematic; maintenance of generators is difficult and the sporadic political unrest that Lebanon has suffered has the potential to interrupt diesel fuel supplies, which would prevent the farmers in this area from undertaking their everyday agricultural activities. Thus this location is ideal for the installation of a solar PV RAPS reducing the disadvantages associated with diesel fuel only based systems, increasing the reliability of energy supply for the farmers at the test site alongside the environmental benefits of decreasing the consumption of fossil fuels. Figure 2 shows a photograph of the RAMseS vehicle. This Multipurpose Solar Tractor (MST) has a dual purpose in that it provides motive power for farmers and additionally is part of the solar PV battery storage system allowing it to be used at the convenience of individuals working in the agricultural sector and simultaneously reducing the costs of electrical energy storage. A low cost electric vehicle would also be useful to provide a clean means of urban transport and other industrial activities currently undertaken by fossil fuel based vehicles which have a low power requirement (< 30 kW).

The PV array was sized according to the incident solar radiation for the location, the energy requirements of the vehicle, the electrical load of the monastery and the current PV technology available on the market. A Photovoltaic array capable of supplying 10 kWp with 3 days of battery storage was installed with a battery supply voltage of 48 VDC at 2000 Ah. The PV array was comprised of 72 PV panels with a maximum power point, maximum power voltage and maximum power current of 138 Wp, 18.2 VDC and 7.59 A respectively, while the open circuit voltage of the PV modules was 22.6 V. The PV modules were

Figure 2
RAMseS Vehicle.

wired in four strings and inclined at a fixed angle of 34° and orientated due south (solar azimuth 0). The battery storage constituted 24 lead acid batteries with a cell voltage of 2 V and a capacity of 2350 Ah, thus the battery storage capacity was 112.8 kWh – the batteries used can undergo more than 2000 cycles [19]. Six inverters were utilised; 4 2.5 kW inverters were used for the PV strings and two central inverters (12.8 kW) were utilised to control the charging regime. The typical number of inhabitants in the monastery is 20 and their daily energy requirement was measured as 0.5 kWh per person per day. To operate the machinery for 10 hectares of viticulture on average 43 kWh per day is needed. Before the RAMseS project commenced the Monastery relied on a diesel powered tractor: Massey Ferguson MF130, for technical details see Larsen *et al.* [17]. The MST had the following characteristics: a mass of 1750 kg, load capacity 1000 kg, main motor power of 12 kW, auxiliary motor 12 kW, maximum torque of 200 N.m and can easily alternate between 2 and 4 wheel drive. The MST has sixteen 6V lead gel batteries on board, total voltage 96 V with a capacity of 180 Ah. The MST has 4 "modes" of operation for on-road and off-road operations: ("Fast" on-road 96 V) 2WD with a maximum velocity of 45 kmh^{-1}, 4WD maximum velocity 30 kmh^{-1} ("Slow" off-road 48 V) 2WD maximum velocity 25 kmh^{-1}, 4WD maximum velocity 10 kmh^{-1}. The on-road range of the vehicle is 70–80 km – it can operate for 2 hours at maximum power and 4 hours when undertaking light duties. The maximum power delivered at the wheel is expected to be 200 N.m. The vehicle has a hydraulic system for external drives and operation of the power drives so that agricultural machinery can be used. Trials of this were firstly conducted in IBMER to determine its performance characteristics and the vehicle was delivered to the test site in July 2009. A photograph of the rear of the vehicle showing the hydraulic system and Power Take off (PTO) shaft and hydraulic couplings is presented in Figure 3.

The following parameters at the test site were measured; ambient temperature (± 0.5°C), incident solar radiation (± 8%), wind speed (± 0.1ms^{-1}), PV cell temperature (± 0.5°C), import of energy to battery array (kWh), export of electricity from battery array (kWh), power generated by PV array (kWh), and battery State Of Charge (SOC). Monitoring of the system commenced in September 2008 and data until the end of June 2009 are presented and discussed in this paper. During this period the MST was not used. This allowed the energy consumption of the test site to be determined. The electric vehicle started to be used at the beginning of August 2009.

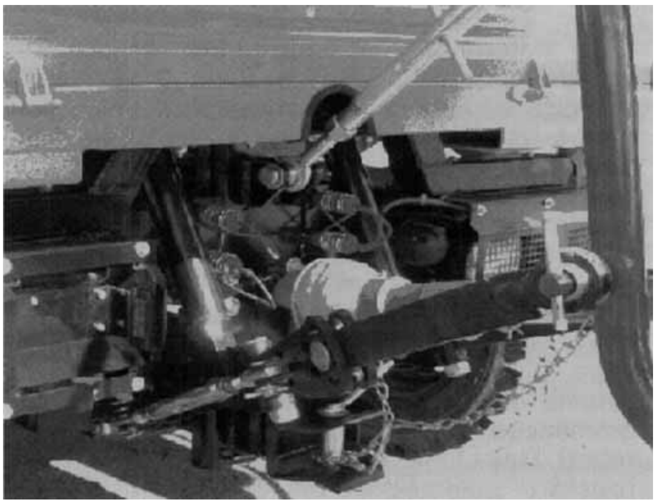

Figure 3 Photograph of rear of vehicle showing PTO shaft and hydraulic transmission.

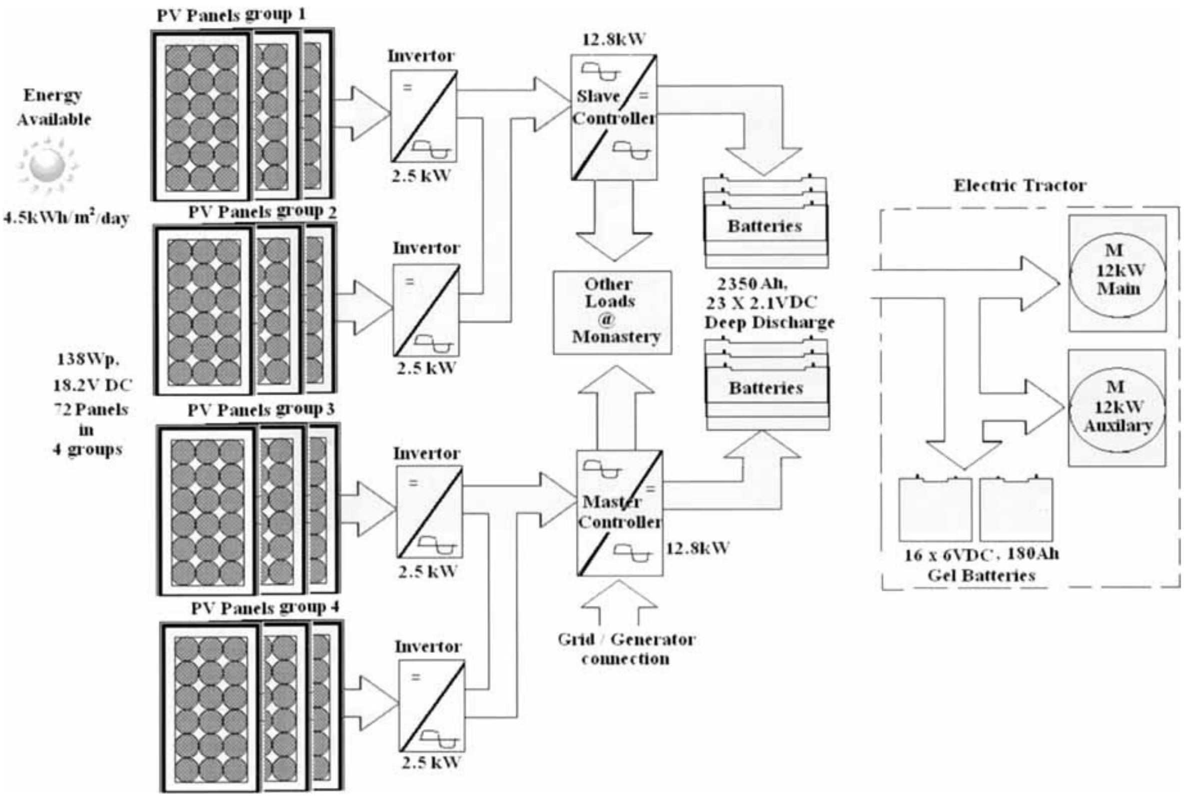

Figure 4 Schematic diagram showing energy flows in the RAMseS system.

Figure 4 shows a schematic diagram of the energy flows within the RAMseS system.

Further information on RAMseS can be found on the project website www.ec-ramses.org [20]). Data from the RAMseS system are presented in this paper and used to extrapolate the impact of such vehicles across Europe. Motive power for RAMseS is derived from battery storage of electricity generated from solar Photovoltaic (PV) arrays.

To determine the contribution of systems towards supplanting fossil fuels a review of Lebanese agriculture was undertaken using field studies, measurements and observations from 1400 farms. Lebanon has two main growing seasons; autumn-winter and spring-summer. In the former, winter cereals (wheat and barley), legumes (chickpea, fava bean) and pulses are mechanically sown from October to November in the southern and central plains of the Bekaa Valley, while in the upper plains of the valley, where rain-fed agriculture is dominant, farming systems still use traditional practices. Harvest commences in March for legumes and ends around May–June when the barley and wheat crops are collected by the farmers. Medium to large sized harvest combines are commonly used for winter cereals, whilst for legumes small-medium sized combines are used. Sowing is typically preceded by seed-bed preparation. However, since the summer period is prolonged (from May to late September) activities such as clod breaking, clearing and harrowing are very common in the pre-sowing period. For the second growing period, potatoes and summer vegetables follow legumes and winter cereals in the cropping pattern calendar. After wheat, potato growing is ranked second in the local cropping calendar, its cultivation being mainly reserved to the vast fertile soils of the central plains of the Bekaa Valley and Akkar plain in the northern part of the country. Potato is planted by mechanical means in March and harvested in late July. A second potato growing season starts in August and ends in November. The aim of having a second growing season for potato is to meet the dietary needs of the population during the winter period.

Production of summer vegetables (tomatoes, cucumber, eggplants, pepper, squash, salads, water melons) is undertaken at inland and coastal regions. Sowing of these takes place in June and the growing season ends in September. Moreover, the transportation of the products to local markets involves the use of tractors (25–66 hp), especially when markets are not far from the point of production, as is the case on the coastal strip, and where also greenhouse production is mainly concentrated. The main mechanised agricultural

Agricultural activity	Minimum Power required (HP)	Minimum Power required (kW)	Work duration (hrs/ha)
Primary tilling and soil turning	84.0	62.7	6.3
Deep tilling (30–60 cm)	84.0	62.7	6.3
Surface tilling (10–20 cm)	65.0	48.5	4.9
De-compaction	65.0	48.5	4.9
Clod breaking/clearing	45.0	33.6	3.4
Seed bed preparation	45.0	33.6	3.4
Land levelling	65.0	48.5	4.9
Harrowing	45.0	33.6	3.4
Rolling	45.0	33.6	3.4
Mowing	45.0	33.6	3.4
Fertilisation and phytosanitary treatment	35.0	26.1	2.6
Sowing and transplantation*	65.0	48.5	4.9
Water transportation in the field	35.0	26.1	2.6
Irrigation equipment transportation	45.0	33.6	3.4
Water pumping from earth ponds	65.0	48.5	4.9
Water pumping from acquifers	85.0	63.4	6.3
Support and field aid techniques	25.0	18.7	1.9
Winter cereals transportation to storage	65.0	48.5	4.9
Potato tuber transportation to storage	65.0	48.5	4.9
Summer vegetables transportation to storage**	45.0	33.6	3.4
Summer cereals transportation to storage	61.0	45.5	4.6
Fruit transportation to storage	61.0	45.5	4.6
Grapevine transportation to brasserie	45.0	33.6	3.4
Olive transportation to press	35.0	26.1	2.6
Land moving, dumping and loading	35.0	26.1	2.6

Period of year: JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

* including drilling and hoeing

** including greenhouse grown vegetables

Figure 5 Main mechanised activities in Lebanese agriculture derived from field study.

activities in Lebanon, and the month in which they must be carried out and their monthly power requirements, were derived from this study and are shown in Figure 5.

From Figure 3 it must be noted that many of these operations have power requirements greater than 24 kW, so for the RAMseS vehicle to undertake any of these the speed of operation must be reduced or higher powered electric vehicles must be produced.

Olive and fruit tree cultivation represents 44% of Lebanese agriculture [21] so due to their importance a more detailed energy audit of olive tree cultivation and viticulture was carried out. This was achieved by measuring the fuel requirements at each month of the year for olive tree cultivation and viticulture for the 1400 farms surveyed in Lebanon, the size of the farms surveyed ranging from 1 – 2 hectares. From the agricultural energy audit it was found that annually viticulture and olive tree cultivation in Lebanon require 1561 kWh/hectare and 1472 kWh/hectare respectively. The monthly power requirements of machinery for olive tree cultivation and viticulture are reproduced in Figure 6.

At the Achkout test site it was calculated that an input of 631 litres diesel Ha^{-1} yr^{-1} was required for cultivation of the grapevines. This figure was then compared to those derived from previous studies detailing the energy requirements of viticulture. A review of work inputs for traditional Mediterranean agriculture [17] reported that agricultural activities such as viticulture and olive tree cultivation required from 80 (non-irrigated) to 130 (irrigated) work days per hectare per annum. This was not broken down into the different

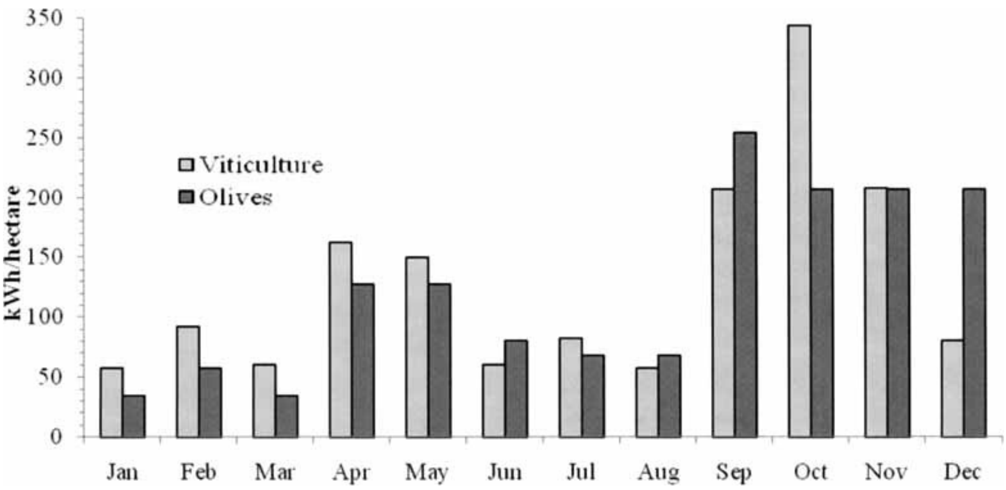

Figure 6 Measured monthly mechanical power requirements for olive tree cultivation and viticulture.

agricultural activities so the fuel requirement per hectare could not be calculated from this information.

The quantity of diesel fuel used for viticulture in the USA was investigated for four locations by Pool, (1980); Central Valley California (irrigated wine grapes), Northern Coastal California (non-irrigated wine grapes), Washington State (irrigated table grapes), and Great Lakes viticulture areas (non-irrigated wine grapes). It was determined that the quantity of diesel required per hectare per year for field operations was 326 litres, 508 litres, 364 litres, and 591 litres respectively [22].

Energy flows within viticulture over a three year period for 5 farms producing grapes in the Tuscany region were studied with the aim of characterising energy consumption within Italian viticulture [23]. The size of the farms investigated was 4.6 ha, 28 ha, 60 ha, 178 ha and 514 ha requiring an annual diesel fuel input of 331 litres ha^{-1}, 217 litres ha^{-1}, 233 litres ha^{-1}, 168 litres ha^{-1} and 132 litres ha^{-1} respectively. Mean fuel usage per annum for the five farms investigated was calculated as 219 litres ha^{-1}.

Fuel constituted 65% to 96% of the total energy input for vineyards that were located in Berisso, Argentina, with 956 litres of diesel ha^{-1} yr^{-1} required [24].

Smyth and Russell (2009) [25], undertook an analysis of energy used in viticulture and the potential for solar energy technologies to replace fossil fuels. It was estimated that globally in 2005 the viticulture industry consumed 105 PJ of energy and was directly responsible for the emission of 16 million tonnes of carbon dioxide. If supporting industries such as bottle making are included then the estimated carbon footprint of the industry was estimated as 76 million tonnes. In 2005; the transport requirement globally for viticulture field operations was reported as almost 29,000,000 GJ. Thus with an area of cultivation of 7.9×10^6 ha, transport energy requirements for viticulture worldwide were calculated as 6.41 GJ ha^{-1} (assuming the calorific value of diesel to be 38.7 MJ/litre, 416 litres per hectare per annum assuming a 23% fuel to mechanical conversion efficiency). Figure 7 shows a visual comparison of these historical energy audits in terms of GJ/hectare per annum required for motive power, together with the study of motive power requirements for viticulture in Lebanon made by the RAMseS project.

From Figure 7 it can be seen that the RAMseS energy transport requirement is within the range of previous studies in this area. Lebanese agriculture requires greater motive power than that used in the USA in 1980 [22], Baldi *et al.* (1989) and Smyth and Russell (2009), calculated as 50%, 20%, 40%, 10%, 70% and 80% respectively of the total required for viticulture in Lebanon. The work presented by Abonna *et al.* (2007) found that viticulture in Berisso, Argentina required 50% more transport energy per hectare. None of these previous reports detailed the monthly distribution of motive power requirements for agriculture. This information is critical for the proper sizing of solar PV systems, as solar radiation and hence available energy is highly dependent on the time of year. As certain other areas of the globe have similar climates this research also has a large replication potential, as it would allow the optimisation of such systems for agricultural purposes helping to reduce the reliance of farmers on fossil fuels. Lebanon was used as a case study and a survey of

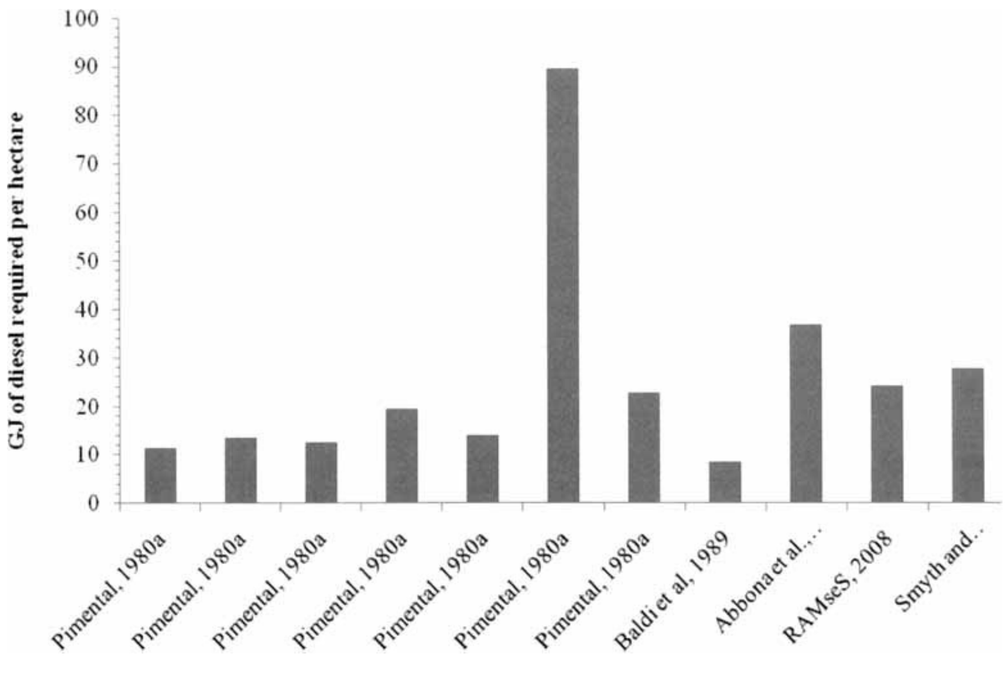

Figure 7
Annual motive power requirements for viticulture derived from previous and current study.

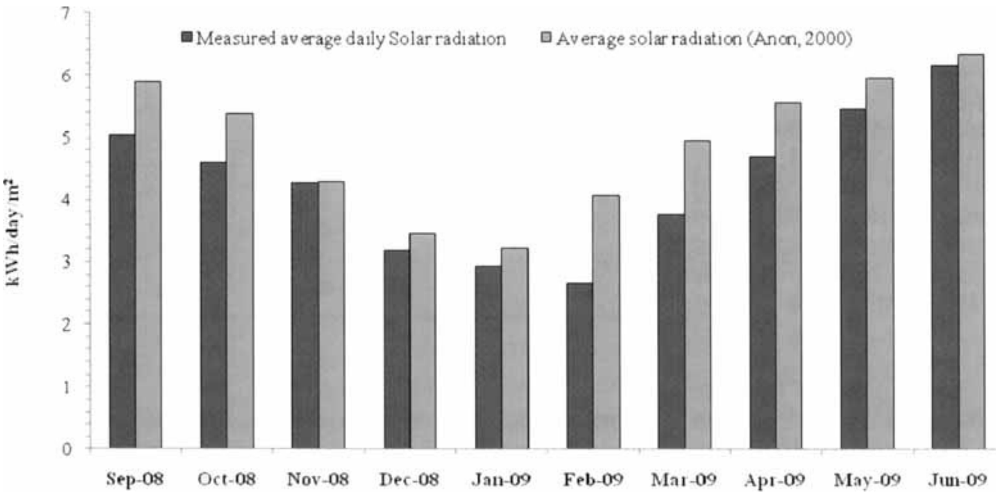

Figure 8
Comparison of measured and long term solar radiation data for RAMseS test site.

all agricultural activities and a detailed agricultural energy audit for each month of the year was undertaken to determine the annual energy distribution for viticulture. This was achieved by measuring the power required for each field operation and determining how long each task took.

RESULTS FROM SYSTEM MONITORING

Results from solar PV system. Initially the system was operated for 10 months without the electric vehicle so that the base load of the monastery could be ascertained. Figure 8 depicts the mean daily values for measured incident solar radiation (kWh/m^2/day), with published values [16] for incident solar radiation (kWh/m^2/day) over the 10 month monitoring period.

The difference between the mean values of measured incident solar radiation is 13% less than the long-term average data [16] over the same time period. The measured data is in reasonable agreement with the long-term average data so this was used to undertake a life-cycle analysis for the system. Figure 9 shows the electrical output of the PV system array output (kWh) and the energy consumption of the monastery (kWh). Over the 10-month monitoring period the PV array supplied 3685 kWh and the monastery consumed 2544 kWh, indicating an annual consumption of 3392 kWh and a mean daily electrical consumption of 9.3 kWh. Typically the monastery has 20 long-term inhabitants indicating that each individual used 0.5 kWh/day.

As the PV array was sized to provide power for the MST not all the generated power could be utilised, as seen in the results presented in Figure 9.

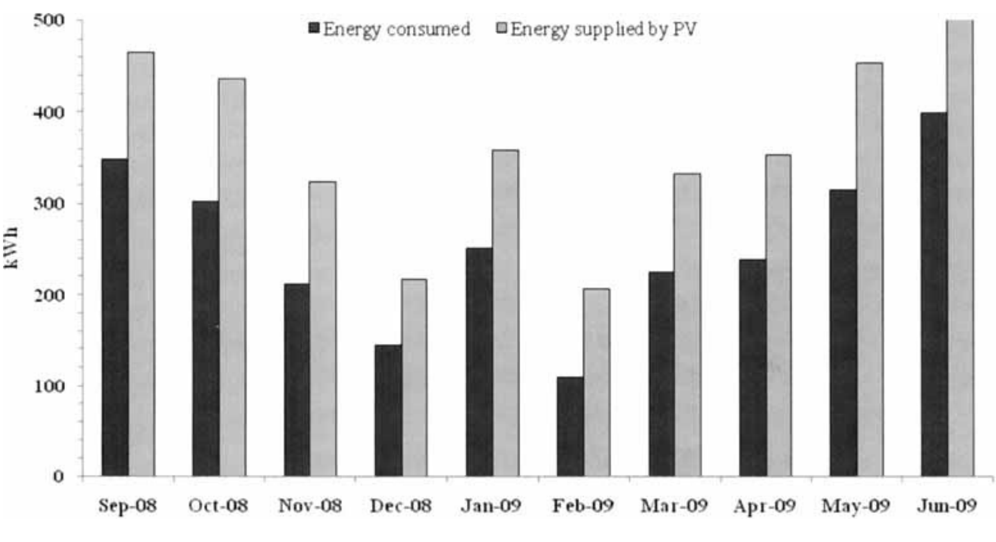

Figure 9
Electrical energy consumption of monastery and energy supplied from PV array September 08 to June 09.

Results of vehicle testing. The MST was tested at IBMER. The maximum range of the vehicle when carrying a driver, travelling at 26.5 km/hr and with a load of 300 kg was measured as 37.6 km. The maximum speed of the vehicle under different conditions is presented in Table 1.

The maximum weight that could be lifted using the three point linkage system was found to be 770 daN. The towing capacity of the vehicle was measured for 2WD and 4WD and battery supply voltages of 48 V and 96 V. The results are shown in Table 2 and a photograph of the vehicle undergoing one of the towing tests is shown in Figure 10.

The maximum rotational speed of the PTO was 569 rpm and 1174 rpm and the maximum pressure that could be exerted by the hydraulic system was 18 MPa.

Table 1 Measured maximum vehicle speed for 96V and 48V and for 4WD and 2WD.

Maximal traction speed	
Condition	Result
4WD forward 48V	10.1 km/hr
4WD reverse 48V	10.9 km/hr
2WD forward 48V	22.6 km/hr
2WD reverse 48V	22.1 km/hr
4WD forward 96V	19.9 km/hr
4WD reverse 96V	not tested
2WD forward 96V	64 km/hr
2WD reverse 96V	not tested

Table 2 Measured maximum towing capacity of Vehicle.

Maximum towing capacity	
Condition	Result
48 V 4WD	863 da N
48 V 2WD	310 da N
96 V 4WD	910 da N
96 V 2WD	340 da N

Comparison of measured output with simple design tools. Figure 11 compares the measured output of the system with that predicted using RETscreen design software [26] over the monitoring period.

The mean difference between measured and predicted data was 15%, corresponding to the 13% difference in measured and long-term average solar radiation. On this basis the RETscreen design tool was selected to estimate the long-term performance data of the PV array at the test site location, allowing a complete life cycle analysis to be undertaken assuming a system lifespan of 30 years. The technical data of the system was then inputted to RETscreen so that the performance of the array could be estimated.

Figure 12 shows the monthly power production of the PV array as predicted by RETscreen when the MST is being used and the energy required for viticulture activities at the Achkout test site. In

Figure 10
MST undergoing a towing test at IBMER.

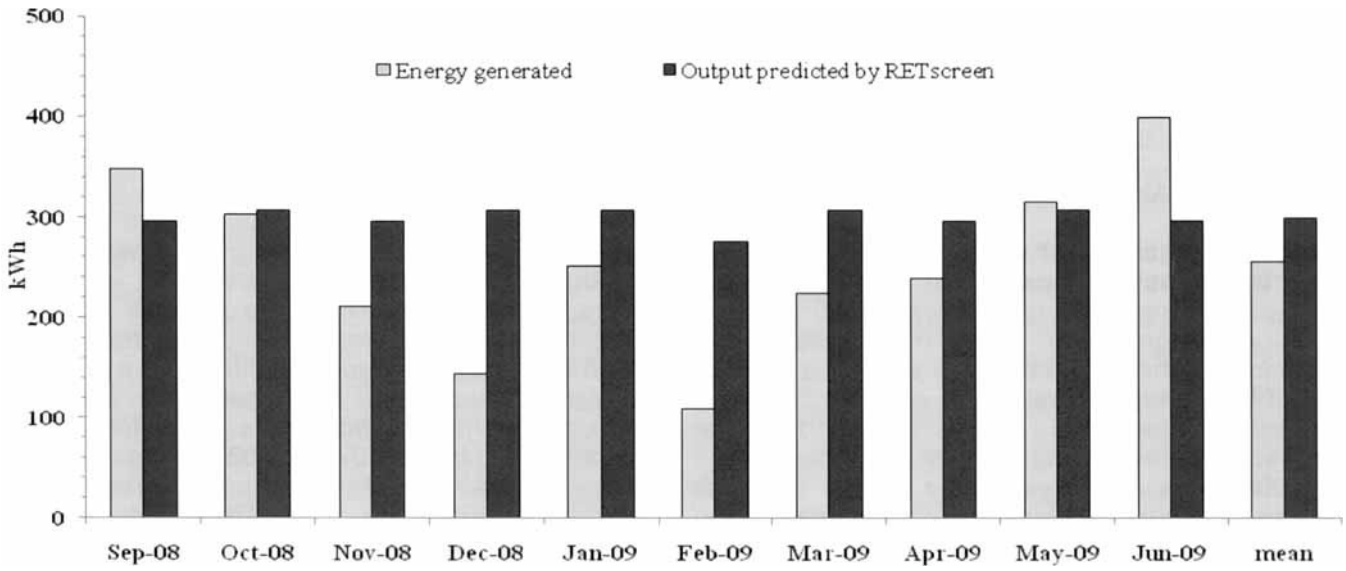

Figure 11 Comparison of measured output of PV system with output predicted by RETscreen.

total, each year the system would supply just over 13000 kWh of electrical power.

From the figures gathered from the agricultural energy audit, the 10 hectares of viticulture at the monastery would require approximately 15611 kWh of mechanical energy annually. Assuming that the RAMseS vehicle can convert 75% of the supplied energy into mechanical energy, the RAMseS system could supply 63% (9835 kWh) of the required mechanical energy. If the conversion efficiency of the conventional tractor used here is 23% [5], [18], then this would give an annual fuel saving of around 4000 litres of diesel fuel. The current cost of diesel fuel in Lebanon is €0.63/litre corresponding to an economic fuel saving per annum of €2520. Additionally other cost benefits will accrue; firstly the RAMseS vehicle has fewer moving parts than a conventional fossil fuel powered tractor, so less maintenance is required; secondly DC electric motors are more efficient

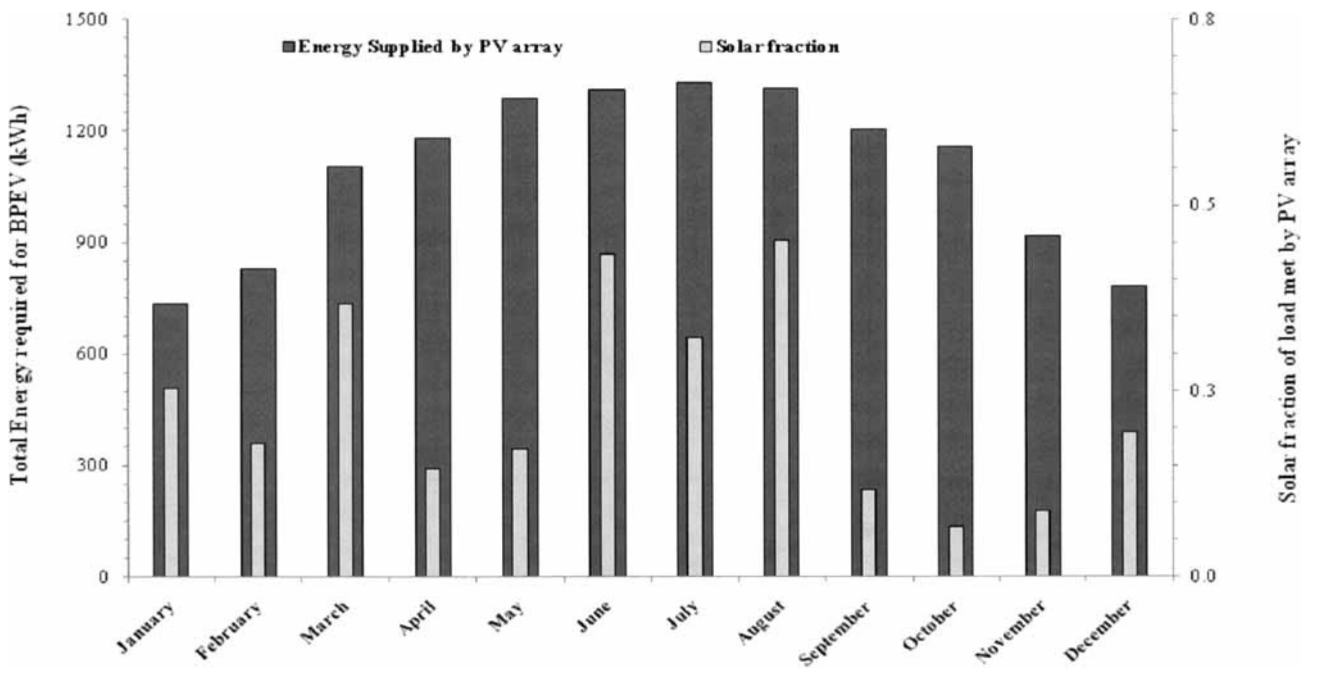

Figure 12 Monthly power output of PV array estimated using RETscreen and solar fraction of motive power load met by BEPV.

than internal combustion engines at part loading [5], [8]), so the fossil fuel based systems can be used at maximum efficiency for tasks which require power levels which cannot yet be supplied from BPEVs.

ECONOMIC ANALYSIS OF RAMseS SYSTEM

Economic analysis of system installed at test site using actual costs. The cost of the PV array, inverters and batteries was €125,000 and it is envisaged that, with mass production techniques, the MST could be sold at a cost of €10000 giving a total cost of approximately €135,000. The simple payback period of the RAMseS system using current fuel costs was calculated as 53.6 years. The simple payback period for the RAMseS system was then calculated for fuel costs ranging from 0.5€/litre to 3€/litre and are shown in Figure 13. The expected life span of the system is 30 years as depicted by the solid line.

The simple payback period was calculated by determining how long the offset in purchasing diesel fuel would offset the capital cost of the system. As the cost of diesel fuel increases the annual fuel saving of the system will increase thus the simple payback period decreases. From Figure 13 it is seen that the simple payback period of the system is less than 30 years when the cost of diesel fuel exceeds 1.1€. As the costs of diesel fuel and interest rates are unlikely to remain the same over the 30 years of the PV arrays projected lifespan, a number of life-cycle saving scenarios were investigated with the Net Present Value (NPV) calculated for fuel increases of 2.5%, 5%, 7.5% and 10% and for discount rates of 2%, 5%, 8% and 10%. It was assumed that the vehicle's batteries were replaced 5 times and the stationary batteries once. The Net Present Value (NPV) of the costs and fuel savings were calculated using Equation 1, and the cost benefit ratios for the different discount rates are reproduced in Figure 14.

Figure 14 shows the conditions under which the economic cost benefit ratio of the RAMseS system is greater than 1 using the costs of the original installation. Over the last 10 years the average inflationary rate across the EU was reported to be 1.9%, [27], implying that if this trend continues the above results using a discount rate of 2% would be the most likely scenario. Looking at the historical increase in fuel prices within the EU from 2002 to 2008 the mean cost of diesel sold (without duty) has increased on average annually by 7.1% Thus, with current economic trends in inflation and if the annual increase in fuel costs increases by just under 3% to 10%, then the original RAMseS system is economically viable.

Economic analysis of system for application in other regions. From Figure 1 it was seen the level of solar radiation varies throughout the Mediterranean region from 4.4 kWh m^{-2} day^{-1} in Spain (Madrid) to 5.9 kWh m^{-2} day^{-1} in Israel (Jerusalem). Thus the annual output of similar sized PV systems would be different at other locations and hence the economic analysis will change. Figure 15 shows the predicted output of the RAMseS system using RETscreen for each of the locations shown in Figure 1.

The cost of the RAMseS installation at the test site was €135,000 i.e. an installed cost of €13,500/kW_p installed PV capacity. As this was a specialised system the cost is higher than for a

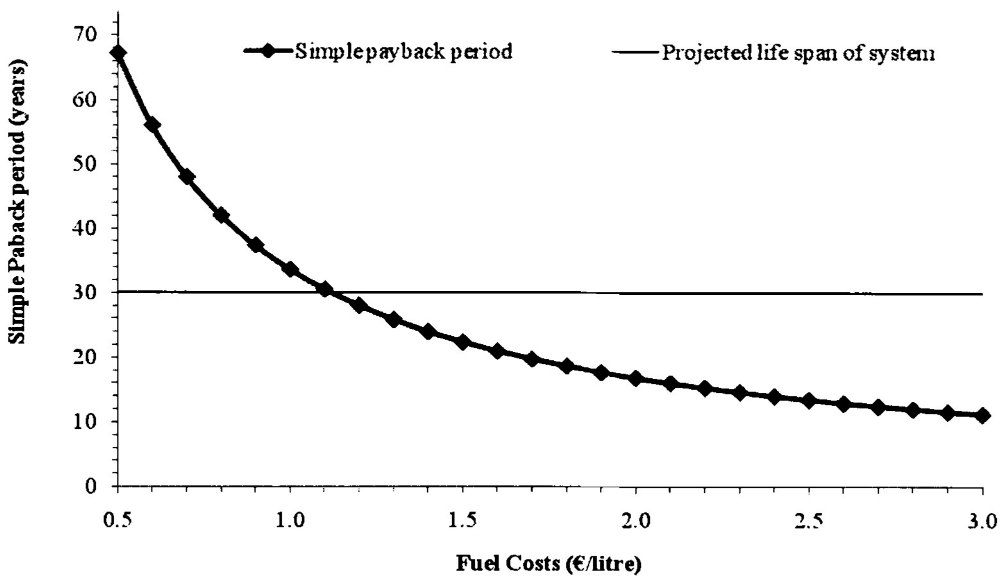

Figure 13
Simple payback period of RAMseS system at test site for various fuel costs.

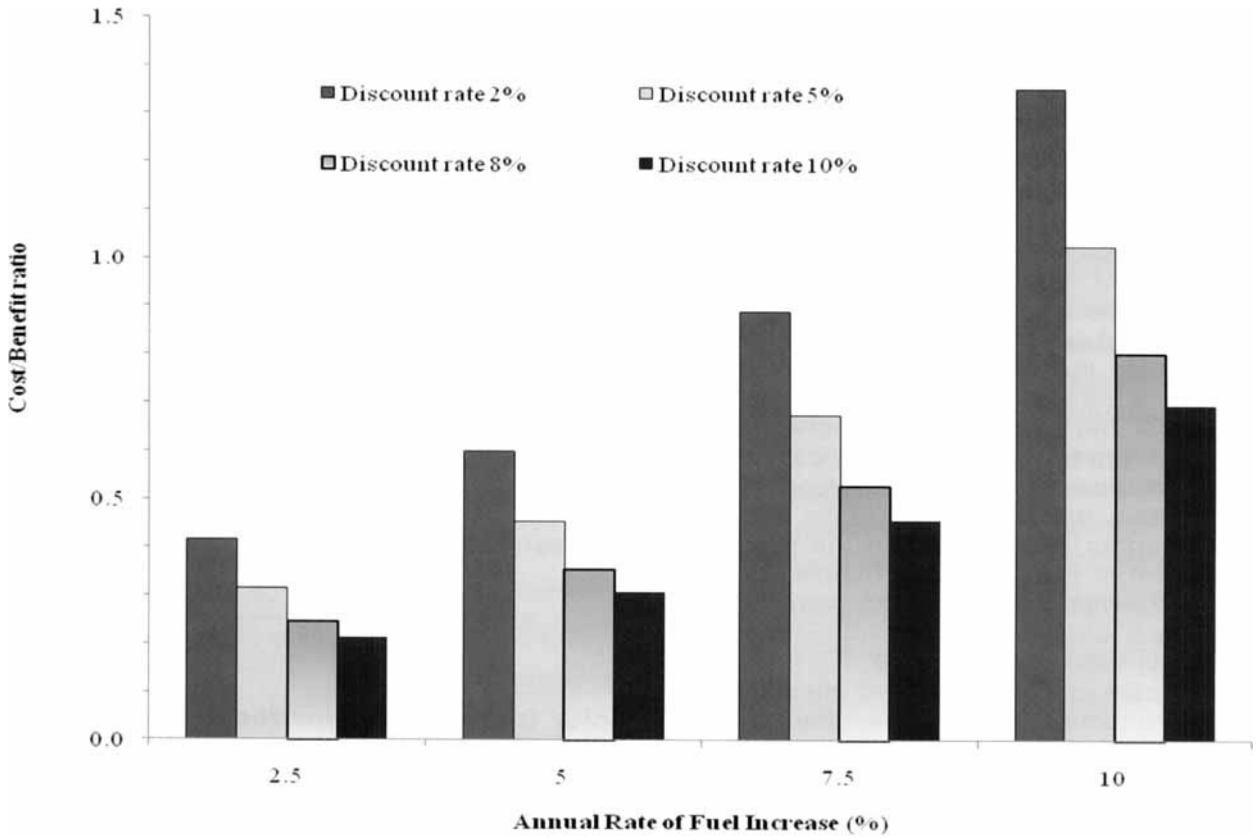

Figure 14 Cost Benefit Ratio of RAMseS system fuel increase rates from 2.5% to 10% and discount rates from 2% to 10%.

typical PV installation. Thus an economic analysis was undertaken assuming a more generic cost for the PV array of €4.23/Wp (Solarbuzz, 2009 [28]), inverter €0.474/W, charge controller (€3.87/Amp) and assuming that lithium-titanate batteries [29] are used with a similar cost to those used in the RAMseS project. Nano-titanate batteries have a number of advantages over lead acid batteries: they can be charged to around 80% of full capacity in ten minutes (assuming charging

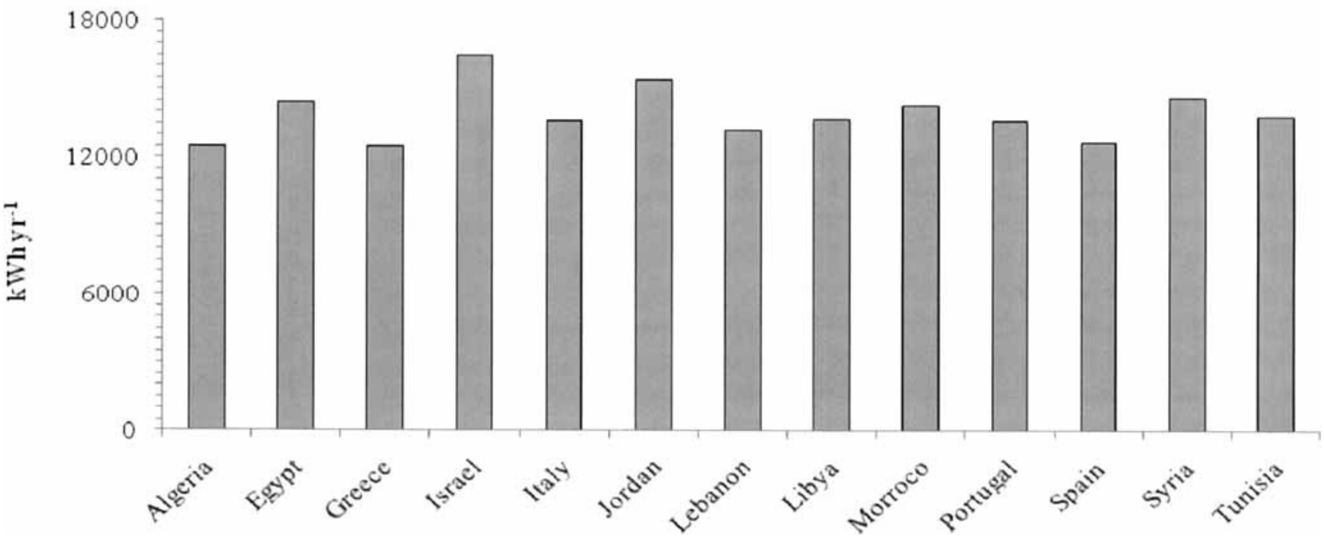

Figure 15 Predicted outputs of RAMseS PV array in Mediterranean region.

current is available), have a lifespan of more than 20 years, can undergo at least 15,000 charge/discharge cycles maintaining 80% of original capacity, and contain no toxic materials or heavy metals (Altairnano, 2009, [29]). Potentially these batteries would outlast the BEPV. With one charge/discharge cycle per day over 30 years, just under 11,000 cycles are required, indicating that these batteries will not need to be changed during the life span of the system, whereas it was estimated that the lead acid batteries would need to be changed at least 5 times. Using the generic market figures for the PV array and power electronics supplied by Solarbuzz (2009) [28] and assuming that the lithium-titanate batteries can eventually be produced at a similar cost to the lead acid batteries used in the RAMseS system for PV systems, the cost of a 10 kWp PV array was estimated as €70,000. Using the predicted outputs shown in Figure 15, the Simple Payback Period (SPP) was calculated for various fuel costs for each of the countries surrounding the Mediterranean sea – see Figure 16.

As the costs of diesel fuel and interest rates are unlikely to remain the same over the 30 years of the PV array's projected lifespan, a number of life-cycle saving scenarios were investigated with the Net Present Value (NPV) calculated for: Fuel increases of 2.5%, 5%, 7.5% and 10% and for discount rates of 2%, 5%, 8% and 10%. It was assumed that the lithium-titanate batteries were used to power the vehicle's batteries and the stationary batteries lasted for the 30 year lifespan of the system. This allowed the economic impact of adopting lithium-titanate batteries as a source of storage and motive power to be determined. The Net Present Value (NPV) of the costs and fuel savings were calculated using Equation (1), and the cost benefit ratios for the different discount rates are reproduced in Figure 17, assuming a cost of €1/litre for diesel (current EU average cost, [4].

The cost per kWh was then calculated for the same scenarios as presented in Figure 17 using Equation (2), as shown in Figure 18.

$$\text{Cost of electricity (€/kWh)} = \frac{\text{(Net present value of costs)}}{\text{(Net present value of electricity)}} \quad (2)$$

Solar fraction and environmental impact of RAMseS. The farm under investigation in this paper has an area of 50 hectares, 10 hectares of

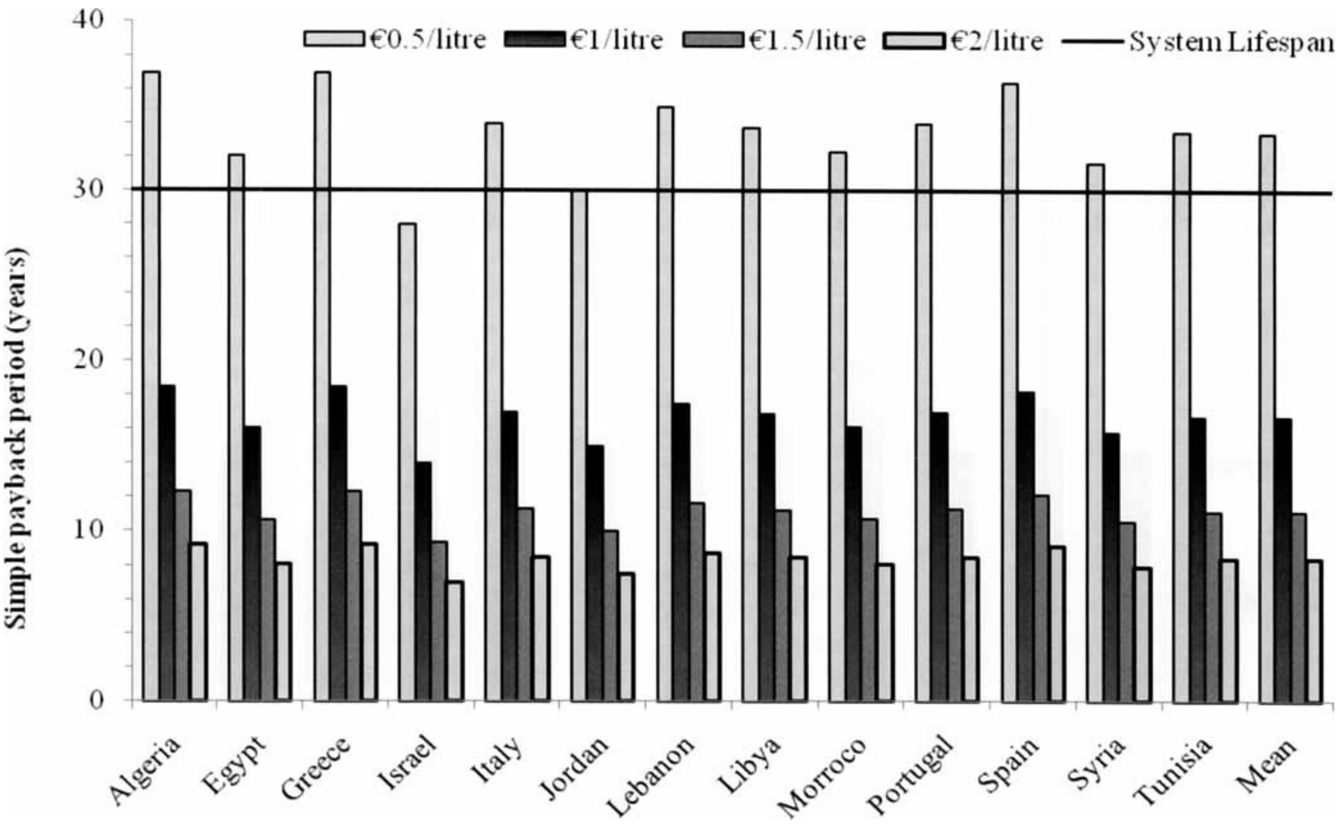

Figure 16 Simple payback period for RAMseS system for various fuel costs using historical data from the Mediterranean region.

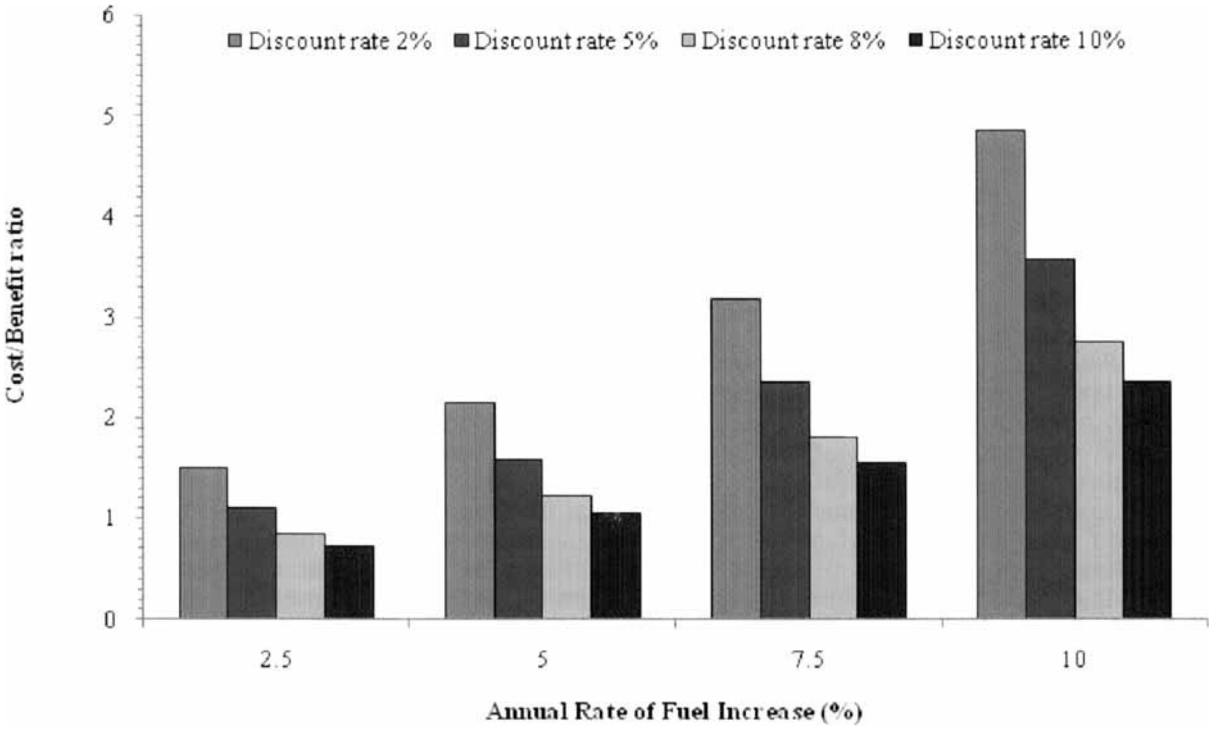

Figure 17 Cost Benefit Ratio of RAMseS system with fuel increase rates from 2.5% to 10% and discount rates from 2% to 10%.

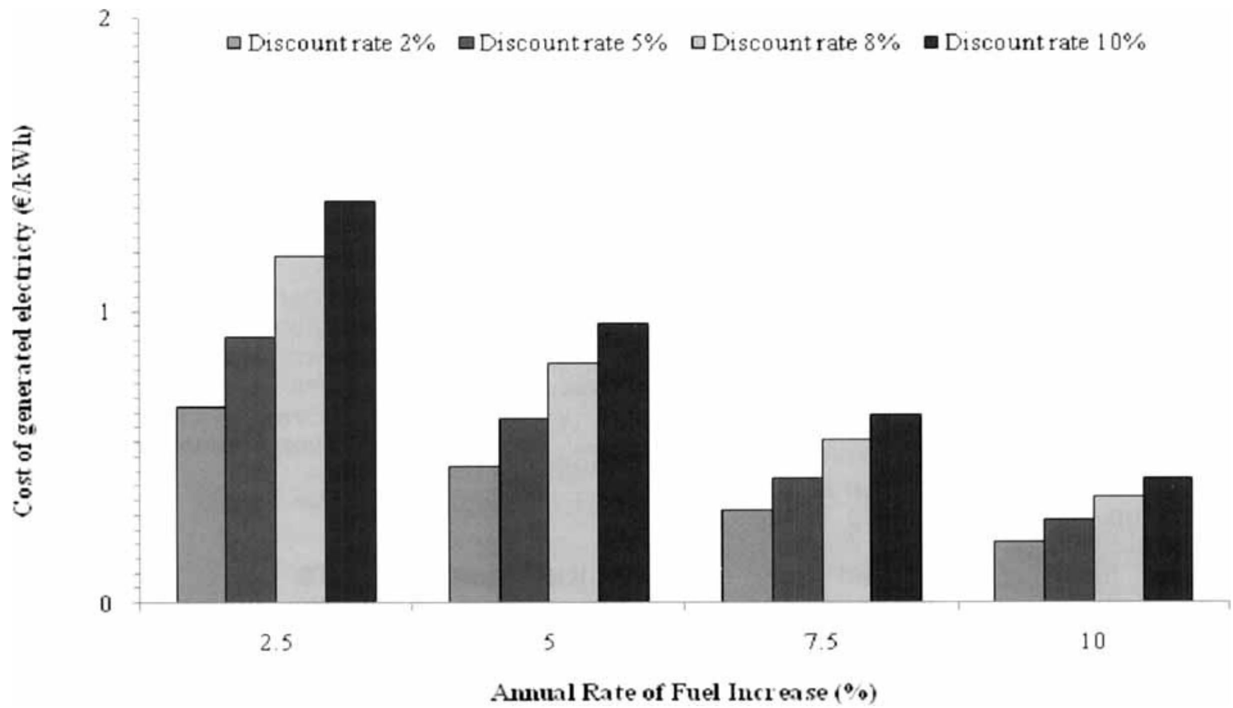

Figure 18 Cost of generated electricity using lithium-titanate batteries for different rates of fuel increase and discount rates.

which is being cultivated as vineyards. From the energy audit undertaken in Lebanon it was estimated that this would require a fuel input of 6310 litres of diesel. The data from other energy audits of viticulture, by Pool, (1980), Baldi *et al.* 1989, Abbona *et al.* 2007 and Smyth and Russel, 2009 and the RAMseS energy audit were averaged to find the mean fuel requirement per hectare for viticulture, calculated as 500 litres per hectare. The average output of a 10kWp PV array in the Mediterranean region was estimated using the values presented in Figure 15 as 14,000 kWh. Thus it was estimated that the RAMseS system will save over 4000 litres of diesel required on average for a 10 hectare area of vineyard located in the countries surrounding the Mediterranean Sea. Using figures supplied by Shaahid and El-Amin (2009), and Shaahid and Elhadidy (2009), it was estimated that each litre of diesel consumed in a diesel engine is responsible for the emission of 0.72 kg CO_2. Thus, from installing a 10 kWp PV array subjected to average Mediterranean climatic conditions, it could be expected that typically a fuel and carbon saving of 4000 litres and 2.9 tonnes per year respectively occurs. Replacement of the current lead-acid batteries would improve vehicle performance, economics (if lithium-titanate can be produced at a similar cost) and also eliminate the emissions of heavy metals such as lead during the vehicle's lifetime.

CONCLUSIONS

Data from an energy audit of Lebanese agriculture was collected and monthly load profiles for olive tree cultivation and viticulture presented. Previous energy audits in this area of agriculture have estimated only annual energy use. If solar PV systems are to be adopted within agriculture for powering BPEVs the distribution of the energy load across the year needs to be determined so that systems are not oversized. Data from September 2008 to June 2009 for the RAMseS system installed at Achkout, Lebanon was collected and found to be in good agreement with the output predicted by the design tool RETscreen. Using the actual and projected future costs incurred for the RAMseS project it was estimated that the PV installation is economically viable for discount rates of 2% and 5% if fuel costs increase by 10% or more, that is only 2.9% higher than the historical increase in fuel cost within the EU in the last 10 years. As the cost of conventional fuels is increased then the attractiveness of alternative energy sources such as solar PV will be increased as greater annual fuel savings accrue. Technically, the testing undertaken by IBMER has shown that this system can augment fossil fuel-based tractors for lighter agricultural duties, thus saving internal combustion engine vehicles for agricultural tasks with a higher power requirement. When the economic analysis was conducted using more generic costs for PV and new lithium-titanate batteries it was estimated that the cost benefit ratio of the RAMseS system was greater than 1, apart from the scenarios of discount rate of 8% and 10% and an annual fuel increase rate of 2.5%. Looking at historical fuel rises, discount rates within the EU and with the adoption of new battery technologies, BPEVs such as the RAMseS system presented in this paper will be economic even when PV is used as a power source. This type of system is particularly appropriate for remote areas where fuel supplies are problematic. Whilst such systems are not able to fully replace fossil fuel powered systems, the vehicle and associated charging system described by this work was found to be able to supply a solar fraction of 63% of the total transport energy required by an established vineyard. One of the problems of using solar powered vehicles with crops harvested on an annual cycle is that harvest usually occurs after the season of peak solar radiation has occurred. Future work will be directed towards: calculating energy profiles for other agricultural crops; undertaking an economic analysis of BPEVs charged from off-peak electricity; undertaking an economic analysis of BPEVs charged from wind-generated electricity; case studies of agriculture within other Mediterranean countries; and the development of a TRNSYS computer model validated from the collected data to allow PV systems suitable for powering electric vehicles for agricultural operations to be further developed and optimised.

NOMENCLATURE

A	Annuity payment (€)
i	Increase rate (%)
d	Discount rate (%)
N	Number of years (yrs)
DC	Direct Current
PV	Photovoltaic
PTO	Power Take Off
RAMseS	Renewable Energy Agricultural Multipurpose System
RAPS	Remote Area Power Systems
GHG	Greenhouse Gases
BEPV	Battery Electric Powered Vehicle
ICEV	Internal Combustion Engine Vehicle
NPV	Net Present Value
MST	Multipurpose Solar Tractor

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