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Techno-economic analysis of innovative production and application of solar thermal chilled water for agricultural soil cooling

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ABSTRACT

Tropical climate countries are net importers of temperate crops due to difficulties encountered in cultivating them, thus constant increase in prices of these crops is always experienced due to increasing demand. To meet the demands, efforts have been made to adapt temperate crops to tropical climate but the crops quality is always low even though at high production cost. Cool greenhouse or upland farming has been deployed in some cases but these are respectively energy consuming and detrimental to mountain ecosystems. Soil cooling is considered to be appropriate in this case to create winter-like soil temperature and to reduce soil water evaporation. Sustainable chilled water production from solar thermal combined power and cooling is presented in this paper to use the (virtually) free solar energy in the tropics to run a combined plant of organic Rankine power and vapour absorption refrigeration cycle thereby generating electrical power together with chilled water production. The study involves the analysis of a sample size soil in Malaysia to determine its cooling load and the plant capacity to overcome the load. The technical analysis is based on the performance of the combined plan over a range of working fluid superheating temperature and the effective solar collector size to supply the needed heat at the range of the temperatures. The economic analysis is carried out (using RETScreen software) by comparing all the associated costs of the present case (using solar energy) with a based case (using power from the national grid) over a 20-year plant life. Analysis shows that 3.5 kW plant size of the present case has a simple payback time of 14.2 years, while 7.0 kW plant size gives simple payback time of 10.8 years. The sensitivity shows that change in investment cost has more influence on viability of the system than electricity cost

1. Introduction

Constant increase in the prices of high-value temperate crops in the tropics is due to difficulties usually encountered in their cultivation. This is occasioned by the high soil and air temperatures, thus forcing the demands for temperate crops to be met through importation. To reduce the expenses on importation, series of efforts have been made to adapt these crops to tropical climate through **cool greenhouse** farming [1,2] which is to condition the planting zone to as low temperature as it is obtainable in the temperate regions, and/or through **upland farming** where soil and air temperatures are similar to that of temperate climate countries. However, in most cases, upland farming results to soil erosion [3–5]. It is also detrimental to the riverine communities as recently witnessed in Cameron highlands (Malaysia). Furthermore, greenhouse farming is an energy consuming system; requiring the cooling of the whole greenhouse air volume. Cooling may also require burning of fossil fuels which is a source of greenhouse gas (GHG) emission. Meanwhile, world Bank 2009 report shows that about 14% of the global GHG emission in CO_2 equivalence come from agricultural practices that involve the use of fossil fuel [6]. For the sustainable temperate fruits and vegetables production in the hot tropical climate lowlands, the following are observably required;

i. Cooling/conditioning of the planting area (cooling system application)
ii. Energy utilization to achieve the cooling and other associated activities

The general effects of soil cooling on planted crops have been investigated by [7], in which soil cooling and supplementary lighting resulted in extension of flower production of the selected cultivars beyond winter period to almost year-round production. Kumejima

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Nomenclature

i) α (soil surface albedo) =0.3 [37]
ii) Q_{inc} (incident radiation)
iii) ρ_a (air density) =1.275kkg/m^3
iv) C_{pa} (air heat capacity) =1.005 kJ/kg/k [65]
v) ρ_w (water density) =1000 kg/m^3 [66]
vi) T_0 (soil temperature) =33 °C
vii) T_a (air temperature) =29.2 °C [63]
viii) r_a (soil-air boundary resistance)
ix) U wind speed
x) Z (reference height) =1.2 m
xi) k (Van Karman constant) =0.4
xii) d=0 for bare soil [67]
xiii) Z_{om}=0. 016 [67]
xiv) q_l (latent heat of vaporization of water) =2270 kJ/kg [66]
xv) ρ_{vo} (soil surface vapour density)
xvi) ρ_{va} (surface vapour density @ the reference height; 1.2 m)
xvii) h_r (height of soil surface roughness =(4×10^{-3})
xvii) $e_{a(t)}$ (water vapour pressure @ reference height) =4 kPa [66].
xix) M_w (molar mass of water) =0.018 kg/mol
xx) R (ideal gas constant) =8.31
xxi) r_p (inner pipe radius)
xxii) t_p (Pipe thickness)
xxiii) d_s (distance between pipe outer surface and soil
xxiv) d_y (distance between the inlet and outlet of the chilled water pipe under the consideration (soil))
xxv) T_{w1} & T_{w2} (inlet and outlet chilled water temperature respectively)
xxvi) N_u (Nusset number) =3.66 [47]
xxvii) m_w (mass flow rate of chilled water)
xxviii) C_{pw} (heat capacity of water)
xxix) h_c (convective heat capacity coefficient at the inner chilled water pipe surface W/m^2/K)
xxx) k_s (thermal conductivity of soil)

Japan [8], demonstrated cultivation of winter crops by pumping cold deep sea water though pipes buried under the soil beds. Sønsteby and Heide [9] conducted studies on the performance of strawberry cultivars in Norway and found out that *'Florence and Korona'* cultivars increased significantly in performance at 18 °C and 15 °C optimum temperatures during the day and night respectively. Although soil cooling has been proven to be technically feasible, its economic viability may still be a problem in the sense that the method of cooling may be energy intensive. For both the cooling and power required to be sustainably and economically delivered in an environmentally friendly manner, this paper presents an ***innovative production and application of solar thermal chilled water*** in which the chilled water is innovatively produced from organic Rankine and vapour absorption refrigeration (ORC-VAR) combined cycle with solar energy as the input and driving force. The renewal of interest in the solar energy utilization for heating and cooling in residential, commercial and public interior spaces, is dated back to early 1970s [10] and in the recent time, solar powered absorption cooling system has been extensively studied by many researchers [11–15] as well as solar powered organic Rankine cycle [16–18]. Each of these two cycles is considered suitable for low-grade thermal energy application [19–21] and attempts have also been made to combine the two cycles in different forms to achieve both power and cooling [22,23] simultaneously. However, in almost all the studies on their combined applications, power generation forms the primary objective. Meanwhile, in the present study, the primary objective is cooling while power generation is considered to complement the system performance. After modeling of cooling load imposed on the soil, the combined (ORC-VAR) system capacity is modeled with reference to the soil cooling load. The two cycles involved in the combined plant use the same working fluid (NH_3-H_2O), thereby reducing the component parts and process complexity. Since most renewable energy project are location specific and the success of similar project in a location does not guarantee the same in another location [24], it is required that the pre-feasibilty and feasibility study of renewable energy project invlove both the technical and economic studies. RETScreen is an important mathematical modeling tool for evaluating the production and application in relation to cost saving, emission reduction, financial viability, and risk analysis of renewable energy project. The software has been widely applied by researchers for these purposes [25–30]. Thus RETScreen is employed in the present study for analysis of the financial viability of the system by comparing the present case with a base case of the same capacity under the same operating conditions.

The main objectives of the study are; (1) to develop models for the radiant soil cooling, and combined cooling and power system that is capable of meeting the load requirement of a dimensioned soil bed, and (2) to assess the technical feasibility and economic viability of the new system compared with conventional systems of similar capacity. Series of studies have been conducted on the soil heat transfer and cooling load imposed by solar radiation heat as well as its effects planted crops (and comfort living), however, they have been focused more on the control of soil temperature through chilled air rather than chilled water with virtually no consideration for solar thermal chilled water application. The inclusion of the economic analysis of the system in this study is to assess not only the direct financially related parameters of the project but also the emission reduction potential of the new system.

The results of an experimental investigation (Table 1) by [31] on the effects of soil cooling (with chilled water) and supplementary lighting on some selected cultivars showed that even though the plant response may be cultivars dependent, but soil cooling and supplementary lighting have marginal improvement on the overall development of the tested crops However, the source of the chilled water for the soil cooling in their experiment was not included in the report. Furthermore, wide and sudden variation in soil temperature due to

Table 1
Effects of soil cooling and supplementary lighting on Alstroemeria cultivars [31].

Plant	Normal flowering period	Treatment and effects	
		Soil cooling	Supplemental lighting
Red sunset	Spring	Flower production started 1 month earlier in 1st year	Early flower production by 2 months
		Combined treatment resulted in 3 months earlier flower production in the 2nd year	
Yellow king	Spring	Negative effect	No effect
Mona lisa	Periodic	Improvement in autumn flower production (in second year)	Remarkable increase in stem yield (second year)
Libelle	Periodic	Year round flower production	Year round flower production
Annabel	Year round	Extension of peak flower production beyond autumn/winter	Higher flower production in Jan and Feb of the second year