Reverse electrodialysis powered greenhouse concept for water- and energy-self-sufficient agriculture

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**Highlights**

- A sustainable greenhouse model is developed to test our concept.
- A case study was produced for Abu Dhabi, UAE, to clarify the concepts efficacy.
- Reverse electrodialysis is shown to be a competitive energy system option.
- Recommendations focus on how the value of this innovation can be captured.

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**Abstract**

This paper documents the development of a sustainable greenhouse system which incorporates a greenhouse, reverse electrodialysis (RED), reverse osmosis, and a dehumidification desalination system aiming to support water and energy self-sufficient agriculture in arid regions with a saline groundwater feed. The system is referred to as the sustainable greenhouse (SGH). The aim is to generate enough fresh water to cover the irrigation load of the greenhouse, symbiotically cool the greenhouse environment to adequate temperatures, and create the energy needed for both. A computational model was first developed to aid in the design of the SGH, and determine its limitations. The model was validated at a commercial greenhouse farm in Abu Dhabi, UAE. Subsequent analysis of the SGH suitability for Abu Dhabi was undertaken, as a representative application region, with the use of a typical meteorological year (TMY) profile created under the study. The main finding from this analysis confirmed that the SGH system can operate if specific design criteria are met. Significant energy consumption in the dehumidification process rendered the system economically unviable if the dehumidifier (condenser) was to supply the full irrigation load. The optimal solution was found to be partial water recovery by the condenser unit, complemented with a reverse osmosis (RO) unit powered using an RED unit. The RED system was designed and tested at lab-scale. Its operation is based on the salinity gradient between seawater and shallow coastal hypersaline groundwater. Design parameters, such as the condenser unit, internal greenhouse shading and fan operations for maintaining suitable greenhouse temperatures were studied. Finally, economic feasibility analysis, which also considers crop selection, was conducted to probe the economic viability of the SGH system.

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1. Introduction

Water security is a global issue. In order to meet global demand in 2050, the International Renewable Energy Agency (IRENA) has estimated that food production will need to increase by 60%, water availability by 55% and energy generation by 80% [1]. It is therefore with pressing urgency that solutions be developed to meet this growing demand.

The provision of freshwater becomes an increasingly burdensome problem for arid regions, whereby inter-related issues like food production, resource security, population growth, and climate...
change are heavily intertwined within the solution hierarchy. Presently, agricultural water demand accounts for only 1.9% of the total installed worldwide desalination capacity [2]. However, ICBA [3] estimate that 15% of farmers in the Arabian Peninsula install small-scale reverse osmosis (RO) plants to desalinate groundwater for field crop irrigation. Fig. 1 shows the salinity levels of groundwater across the Emirate of Abu Dhabi as reported by EAD [4]. It is important to note the hyper-salinity of the coastal aquifer, ranging from 100,000 to 125,000 ppm, almost three times the salinity of Gulf seawater (SW). The depth of groundwater in the coastal aquifer is typically less than 5 m below sea level [5]. The hyper-salinity of groundwater prevails in most eastern coastal areas of the Arabian Peninsula [6], making the coastal groundwater impossible to use directly for irrigation, or even desalination.

The issue of food security is of pressing concern within the Arabian Gulf region. This has led to the relentless quest for sustainable agricultural systems in this region that can produce food, but not lead to excessive consumption of water and energy resources.

Greenhouses are already a recognized solution for food production, with some 5.4 million hectares of greenhouse area installed globally, which currently produces 60% of the vegetables consumed globally [7]. Providing a controlled environment that has been engineered to operate in otherwise restrictive conditions, as compared to open field cultivation, provides the opportunity for agricultural systems to operate with significantly less risk. The introduction of modern irrigation and agricultural techniques has led to a noticeable increase in agricultural yields per unit of irrigated land and unit of water in arid regions [8]. There is an opportunity for a larger agricultural sector in arid regions with growing economies, such as the Gulf Cooperation Council (GCC) countries and there is a need to make it sustainably viable in the given environment. The sustainable greenhouse (SGH) concept examined in this paper aims to achieve both goals symbiotically.

1.1. The sustainable greenhouse (SGH) concept

The SGH system reported in this paper uniquely combines and builds on existing research in solar powered desalination, seawater greenhouse technology, saline agriculture, reverse electrodialysis (RED) and food-water-energy nexus solutions. The greenhouse performs like a solar still while simultaneously providing a controlled environment suited to the cultivation of crops. The presence of this solar still embodies a solar humidification-dehumidification desalination system. By using sunlight, saline groundwater and the atmosphere, the system produces fresh water and cool air, creating more temperate conditions for the cultivation of crops. Thus, mimicking the natural hydrological cycle in a region where the environment is not sufficient to provide a sustainable agricultural system.

The proposed SGH system is intended to make use of the vast areas of coastal desert land with abundant saline groundwater resources in countries along the eastern coast of the Arabian Peninsula. The controlled environment of a greenhouse is an important first step. Fernandes et al. [9] estimated that the elevated humidity inside a greenhouse leads to a 60–80% decrease in water consumption versus open field irrigation. Although evaporative cooling is suited to arid regions [10,11], the gain in water efficiency in a greenhouse can be lost due to the presence of an open cycle evaporative cooling [12]. Incorporating a dehumidifier/condenser is an important design feature to recover fresh water for irrigation. This is an example of leveraging symbiosis in the design, as the driving force behind the procurement of the freshwater component is the incidence of solar radiation on the greenhouse.

Several variations of what is referred to in literature as the “seawater greenhouse”, already exist [13–16]. The layout of our SGH system took lessons from each of those projects and theoretical studies, to produce a concept which can self-sufficiently produce

Nomenclature

AEM anion exchange membrane
CEM cation exchange membrane
BNI beam normal irradiance
DHI diffuse horizontal irradiance
EHF emirates hydroponics farms
ET flux of evapo-transpired water vapour from plant canopy area (kg/s/m²)
Elt evapotranspiration flux (W/m²)
GHI global horizontal irradiance
GW groundwater
H enthalpy (kJ/kg)
Id current density (A/m²)
Is incoming shortwave solar radiation (W/m²)
Ktube thermal conductivity of condenser tube (W/m-K)
l leaf characteristic dimension (m)
LAI leaf area index
M mass flow rate (kg/s)
MP membrane pair
OCV open circuit voltage (V)
Pd power density (W/m²)
Q heat transfer rate (kW)
Re external crop resistance (s/m)
Ri internal crop resistance (s/m)
RED reverse electrodialysis
Rsw net shortwave radiation (W/m²)
RO reverse osmosis
Rstack internal stack resistance (Ω)
SCAD Statistics Centre Abu Dhabi
SGH sustainable greenhouse
SW seawater
TDS total dissolved solids
TMY typical meteorological year
U Heat transfer co-efficient (kW/m²-K)
VPD Vapour Pressure Deficit (Pa)

Greek symbols

γ psychrometric constant (Pa/°C)
δ slope of the saturation curve of the psychrometric chart (Pa/°C)
λ latent heat due to water vaporization (kJ/kg)
ρ density (kg/m³)
Ω resistance
τ transmissivity of greenhouse cover material to solar irradiation
φ relative humidity (%)
ω specific humidity (kg water vapour/kg dry air)

Subscripts

1, 2, 3, 4... stream number
A dry air
cover greenhouse cover material
cpc plant canopy
csun solar radiation
cw water
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