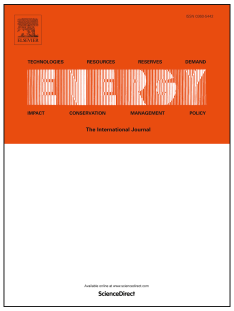

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A two-level decision making approach for optimal integrated urban water and energy management

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Abstract

A spatial-temporal model is proposed for optimal integrated water and energy resource management in urban areas, considering daily surplus output from residential grid-connected rooftop photovoltaics as an energy source for sustainable supply. The model addresses optimal investment and operational decisions of a desalination- based water supply system driven by surplus photovoltaic output and grid electricity. The two-level mixed integer linear programming model considers demands, systems configuration, resources capacity and electricity tariffs and gives the solution such that the highest compatibility with available renewable energy is achieved. The model is then applied to Perth, Australia and solved for three operational scenarios. The results show, for a given year, hourly (flexible) basis scenario leads to $9 521 425 and $18 673 545 economic benefits over seasonal (semi-flexible) and yearly (fixed) basis scenarios, respectively. They also indicate 19.9% better economic performance in terms of annualised unit cost of water production over existing Southern seawater desalination plant in Perth. Additionally, it is shown that the seasonal change on the optimal solutions mainly corresponds to the share of each energy resource to meet water-related energy demand. Finally, the results indicate higher sensitivity to the variation of the photovoltaic installation density compared to financial rate.

Keywords: Optimisation, Photovoltaics, Grid electricity, Desalination, Urban water supply

1. Integrated urban water and energy management

Diminishing natural water resources, increasing population growth and rapid urbanisation more than ever highlight the necessity of deploying drought-proof technologies such as desalination for secure drinking water supply in urban areas. in fact, in some arid and semi-arid regions such as Middle East and Australia, these technologies contribute significantly in urban water supply. However, the energy intensity of these technologies is one of the main obstacles to turn them into the first priority among existing water supply options.

Constant advance in desalination technologies has made it possible to address the issue by considering renewable energies for water-related energy demand. However, to deal with the intermittency of renewable energies and consider such water supply systems as a sustainable solution, the optimal integrated water and energy management is essential. In this context, optimisation is a strong tool that can be applied to find investment options and operational scheduling to provide the most system compatibility and consequently resulting in the least total cost.

There are numerous optimisation studies on integration of desalination plants with renewable energy sources at the point of production. These studies have addressed the optimal investment or operational decisions of the system at the scales of a unit or a multi-utility plant. At a unit scale, Shalaby [1] have reviewed the studies on reverse osmosis (RO) desalination powered by photovoltaic (PV) and solar Rankine cycle power systems including optimisation models. Similarly, Ref. [2] has presented a review on optimisation studies using renewable energies to power membrane-based desalination process. The studies on different desalination process driven by various renewable energy sources (solar, geothermal, wind and ocean energy) have been reviewed in Ref. [3]. At the scale of a multi-utility plant, Perković et al. [4] have addressed the optimal energy flows in a hybrid energy system coupled with desalinated water production and storage using linear programming (LP). Bourouni et al. [5] and Ben M'Barek et al. [6] have proposed a model based on the genetic algorithms to address the optimal configuration of the integrated RO desalination process with diverse combinations of energy units (i.e. PV panels, type and number of batteries). Clarke et al. [7], have addressed the optimal sizing and techno-economic assessment of a stand-alone renewable energy sources integrated with desalination unit under static and dynamically changed water demand and compared the optimal solutions derived from intelligent techniques (particle swarm optimisation) with HOMER software. Rubio-Maya et al. [8] proposed a mixed integer non-linear programming (MINLP) model for the optimal selection of the system configuration and sizing of the integrated system among different possible candidates. Also, in Ref. [9] , authors compared the economics of different size and configuration of small-scale RO system with hybrid energy sources (solar/wind/diesel) using simulation model coupled with optimisation methods (Nelder-Mead simplex as well as genetic algorithms for different problem formulations). In addition, there are several studies that have addressed simultaneously optimal investment and operational decisions of the integrated system. For instance, at unit scale Antipova et al. [10], have applied multi-objective MINLP model for the optimal design of a RO plant integrated with solar Rankine cycles and thermal energy storage as well as scheduling of the energy flows in the thermal energy storage. At the scale of multi-utility plant, Segurado et al. [11] have applied a derivative free multi-objective optimization method (Direct MultiSearch) to optimise the size and operational strategy of a wind powered desalination plant and a pumped hydro storage system to address both water and energy supply. The mentioned studies provide a valuable insight into the optimal design and operational scheduling of the integrated water supply units with renewable energy sources. However, they generally miss the broader perspective of water supply system, from the production point to the end use, which is needed in practice, for holistic optimisation of the system and therefore sustainable supply.

There are a few studies considering all main components of the desalination-based water supply system in a holistic way. These models have been mainly developed at national and regional scales. For instance, in Refs. [12, 13], authors have developed a LP model for the optimal scheduling of the main components of a desalination-based water supply system fuelled by hybrid energy sources including water production, storage and transfer at a national scale. In Ref. [14], the optimal economic dispatch of water and energy networks including water and power plants, co-generation plant and hybrid energy sources has been addressed using a mixed-integer quadratic constrained program. In another study, Saif and Almansoori [15] have applied a mixed integer linear programming (MILP) model for the optimal capacity expansion of the integrated water and power supply chain taking into account renewable power plants at a regional scale. These studies have addressed either the operational decisions of the supply system or investment decisions, taking into account yearly operational details. However, in order to move towards an affordable and sustainable supply system and to ensure the validity and robustness of the decisions, it is necessary to specify the optimal investment decisions together with their short-term operational considerations.

To the best of our knowledge, there is no optimisation study at a city scale addressing simultaneously investment and short-term operational decisions of the desalination-based water supply system fuelled by hybrid energy sources (fossil fuels and renewable energies) in a holistic way while capturing both spatial and temporal aspects of the problem. The following section explains the problem, which this study addresses in order to fill the mentioned knowledge gap in the existing optimisation models in the context of the integrated water and energy management.

2. Surplus residential grid-connected photovoltaics output, as an energy source for urban water supply system

Installation of grid-connected PVs on residential rooftops can have a significant share in the urban energy mix. In land-restricted urban areas, small-scale rooftop PVs have the privilege of being space-saving compared to centralised solar farms and can perform efficiently due to being close to the point of load [16]. However, the extent of their installation is generally limited to the hosting capacity of the existing electrical grid to deal with the intermittency of surplus PV output fed to it. This surplus PV output is the result of the mismatch between supply and demand, which usually occurs during a day in urban residential areas.

In this regards, electricity storage technologies such as batteries on the demand side have been widely proposed in the literature to combat this issue. These studies include both techno-economic analysis and optimisation of the PV-battery system. Mulder et al. [17] have provided a complete investment analysis to achieve the optimal PV-battery system considering the subsidy systems and electricity price. Hoppmann et al. [18] have reviewed the studies addressing the economics of batteries integrated with small-scale PV systems and investigated the profitably of the integrated PV-battery systems with diverse capacities under different electricity price scenarios. Recently, Linssen et al. [19] have applied a battery-PV-simulation (BaPSi) Model for techno-economic analysis and cost-effective configuration of the integrated system considering different consumer load profiles and electricity tariffs. In Ref. [20], authors have reviewed the developed optimisation models for design of the PV-battery systems and presented a multi-period MILP model for optimal configuration and size of such system incorporating the operational decisions. In another study, Ranaweera and Midtgård [21] have addressed the energy management system of an integrated PV - battery system and applied dynamic programming to solve the associated non-linear constrained optimization problem. Sani Hassan et al. [22] have optimised the power flows among different components of grid-connected PV –battery system using MILP model integrated with distributed energy resources customer adoption model (DER-CAM) software tool. Pena-Bello et al. [23] have applied a genetic algorithm for optimal scheduling of battery storage integrated with grid-connected residential PVs for two applications of PV self-consumption and demand-load shifting under different electricity tariff structures. In a recent study, Wang et al. [24] have solved a discrete LP problem for energy management of a shared battery storage between customers and local distribution network operators under variable electricity tariffs.

These studies emphasise on the benefits of electricity storage systems in terms of protecting the electrical grid from the intermittent electricity penetration and saving the surplus PV output for later use. However, the application of small-scale batteries at household level is still subjective and depends highly on government support through decreasing costs of these systems and implementing feed-in tariffs (FiT) as well as increasing retail electricity prices [25].

An alternative to electricity storage technologies is to create compatibility between load and supplied electricity at the time of electricity generation. In the context of integrated urban water and energy management, this can be achieved by considering the components of a desalination-based water supply system as deferrable loads to the electrical grid [12, 26]. In other words, operational scheduling of different components of water supply system, including desalinated water production, storage and transfer, can be adjusted such that it can use the most out of available surplus PV output. This approach, therefore not only benefits the energy sector but also contributes to sustainable delivery of water.

In our previous study [26] a LP optimisation model was presented for operation of a desalination-based water supply system driven by daily surplus PV output and existing grid electricity system taking into account both temporal and spatial characteristics of the problem. The model was solved for an urban area considering electricity cost tariffs in the formulation of the objective function to address the interaction between two sides of water and energy supplies. However, there are still several questions, which needs to be answered: 1. How does different system operational scheduling affect the investment decisions of the desalination-based water supply system driven by grid electricity and surplus PV output? 2. What is the impact of different operational scheduling on the share of various energy sources (grid electricity vs. surplus PV output) in meeting the demand? and finally 3. To what extent are the optimal decisions varied by seasonal change, PV installation density and financial rate?

This study is essentially built upon our previous study [26] including more details on desalination-based urban water supply system components, electrical grid considerations and financial aspects to answer the above-mentioned questions and therefore contributes to fill the research gap described in Section 1. Accordingly, a temporal-spatial optimisation model proposed in this paper, addressed both optimal operation and investment decisions of a desalination-based water supply system driven by daily surplus PV output in conjunction with grid electricity such that the most compatibility with available renewable energy is achieved with minimum annualised total cost. Three tools of geographical information system (GIS), system advisor model (SAM) and Excel were integrated with a two-level MILP model to determine the optimal desalination plants capacity, storage tanks size and their locations as well as a pipeline network. The optimal scheduling of the system consisting of water production, storage and transfer was also addressed. The model was then applied to an urban area located in the north-western corridor of Perth, Western Australia (WA) for three operational scenarios in order to demonstrate the capabilities of the model and complete a sensitivity analysis.

The remainder of the paper is as follows: section 3 states the problem and the modelling strategy. The mathematical formulation is explained in section 4. Section 5 describes the model parameters associated with the case study. The optimal solution in alternative operational scenarios, comparison of the results with existing desalination plant and the sensitivity analysis are discussed in section 6. Lastly, section 7 presents the concluding remarks.

3. Problem statement

The problem is described for an urban area located at arid region as follows:

i) A planning horizon of one year (t) is divided into 4 seasons (s), such that for each season a representative day with 24 time blocks (b) is considered. In order to simplify, for the rest of the paper, the term “time period” is used to refer to the whole time expression of a time block b in season s and year t .

ii) The entire area is split into several zones (i). In each zone and time period, water demand ($D^{w}_{t,i,s,b}$ (m^3)) is supplied by desalination-based water supply system. Residential energy demand ($D^{er}_{t,i,s,b}$ (kWh)) and water-related electricity demand are provided through the combination of PV output and grid electricity. It is notable that water-related electricity demand varies depending on the operational scheduling and is calculated through the optimisation model, based on electricity demand per unit of water produced (D^{ep} (kWh/m^3)) and transferred ($D^{ewt}_{i,j}$ (kWh/m^3)).

iii) Desalination-based water supply system is composed of desalination plants, storage tanks and a pipeline network. For a given zone, desalination plant design capacity of AC_c (m^3/day) with associated capital cost of $CapDQ_c$ (\$) can be selected to produce the required water. The plant factor of PF is taken into account to allow the ample time for preventive maintenance and unforeseen shutdowns. This factor equals to the number of days the plant operates divided by the total number of days in the planning horizon and assumed to be the same for all desalination plants. The average operational and maintenance (O&M) cost per unit of desalinated water produced (C^{OM}_{t} (\$/m^3)) is considered for all plant design capacities.

iv) In each zone equipped with a desalination plant, a storage tank can be located in the relative population centre to store extra produced water. The size of the storage tank (ST_m (m^3)) is chosen taking into account the maximum and minimum allowable stored water ($MaxS_{t,i}$ (m^3) and $MinS_{t,i}$ (m^3)). While for each storage tank size, there is a specific capital cost ($CapSN_m$ (\$)), for all storage tanks sizes, an average O&M cost per unit of stored desalinated water (C_t^s (\$/m^3)) is considered.

v) The amount of produced water that can be transferred between any two allowable zones ($L_{i,j}^w$) or between the desalination plant and storage tank within the same zone, depends on the maximum pipeline capacity ($MaxTW_t$ (m^3/day)). In this study, only one pipe size with capital cost per unit length of $CapWT$ (\$/km) is considered for water transfer among allowable zones or within a zone.

vi) The existing electrical grid delivers the required electricity through distribution substations. The maximum electricity that can be transferred to each zone is determined by the maximum capacity of the associated substations ($MaxPS_{t,i}$ (kW)) considering a power factor. Another energy source is residential rooftop PVs providing renewable energy for the given area. The maximum possible PV output for each zone ($MaxR_{t,i,s,b}$ (kWh)) is set based on PV installation density (k_1 (%)) defined as the number of households equipped with PV systems in each zone divided by the total number of households in the same zone. It is notable that in this paper, the same installation density is considered for all zones.

vii) In order to take into consideration the interaction between water and energy supply authorities, electricity cost tariffs are used. The grid electricity price follows the time of use (TOU) tariff structure and is divided into fixed and variable electricity supply charge for residential and business (water supply) sectors. Fixed electricity charges (C_t^{fer} and C_t^{feb} (\$/day)) are considered to be constant during the planning horizon while variable electricity charges ($C_{t,s,b}^{er}$ and $C_{t,s,b}^{eb}$ (\$/kWh)) are defined in terms of the amount of electricity used in each time period. For surplus PV output usage, variable electricity charge of C_t^{rb} (\$/kWh) is applied based on the net FiT. This is assumed to be the electricity price that business sector (water supplier) needs to pay if it operates the system such that it can be more compatible with available surplus PV output.

Accordingly, the following key decision variables are determined by the model:

1. Desalination plants design capacities, storage tanks sizes and their locations in the planning horizon

2. Desalination plants water production schedule in each time period

3. Water storage and transfer among allowable zones in each time period

4. The share of grid electricity and surplus PV output to meet energy demand of different components of the water supply system

Such that the total water and energy demand (both residential and water supply system) is satisfied and the annualised total cost of the system is minimised.

Fig. 1 illustrates the structure of the proposed model. The inputs and results of each analysis are presented in blue and green boxes, respectively. Yellow boxes show the applied analysis. Red and purple boxes depict, in order, the main constraints and objective function of each level of optimisation.

4. Mathematical formulation

In this section, an MILP model is presented to address the optimal investment and operational decisions of a desalination-based water supply system fuelled by daily surplus PV output and grid electricity such that available renewable energy is used at maximum possible level and the annualised total cost of the system is minimised.

4.1. Level-one optimisation

The level-one optimisation assists to determine the surplus PV output potentially can be assigned to water-related electricity supply. The formulation of the model at this level of optimisation is described in the following sections.

4.1.1. Objective function

The model consists of two objective functions. The level-one objective function represents the optimal allocation of each electricity source (grid electricity and PV output) to residential electricity demand equipped with PV system such that their total electricity cost is minimised (Eq. (1)):

$$Min\ z_1 = \left[\sum_t \sum_i \sum_s nd_s . \sum_b C^{er}_{t,s,b} . P^{r}_{t,i,s,b} + dur_b . convf_1 . C^{fer}_t \right] \tag{1}$$

Where, nd_s (day) is the number of days in each season, $P^{r}_{t,i,s,b}$ (kWh) represents the share of grid electricity in meeting residential electricity demand equipped with PV system, dur_b (h) is the duration of the time block b, and $convf_1$ (day/h) is a conversion factor.

4.1.2. Electricity balance

In each zone and time period, the balance between electricity sources and electricity demand of households equipped with PV system ($k_1 . D^{er}_{t,i,s,b}$) is expressed by Eq. (2):

$$P^{r}_{t,i,s,b} + RE^{r}_{t,i,s,b} = k_1 . D^{er}_{t,i,s,b} \quad \forall t, i, s, b \tag{2}$$

Where $RE^{r}_{t,i,s,b}$ (kWh) is the share of PV output in satisfying residential electricity demand equipped with PV system.

4.1.3. Energy resources capacities

For each zone and time period, the grid electricity assigned to residential electricity demand equipped with PV system is limited by the maximum capacity of the associated zone substations ($MaxPS_{t,i}$ (kW)) multiplied by the duration of the time block b (dur_b (h)) (Eq. (3)):

$$P^{r}_{t,i,s,b} \le dur_b . MaxPS_{t,i} \quad \forall t, i, s, b \tag{3}$$

Likewise, the upper bound of the PV output assigned to the electricity demand of households equipped with PV system is given by Eq. (4):

$$RE^{r}_{t,i,s,b} \le MaxR_{t,i,s,b} \quad \forall t, i, s, b \tag{4}$$

4.2. Level-two optimisation

The outcome of the level-one optimisation is stored in two auxiliary parameters, namely grid electricity assigned to electricity demand of households equipped with PV systems ($PP^{r}_{t,i,s,b}$ (kWh)) and surplus PV output fed to the electrical grid ($Surp_{t,i,s,b}$ (kWh)). These parameters are then applied to determine the remaining capacity of each electricity source that can be potentially allocated to the water-related electricity demand in the next level of optimisation. The details of the level-two optimisation are presented in the following sections.

4.2.1. Objective function

In level- two optimisation, the maximum exploitation of surplus PV output to supply water-related energy demand is achieved. At this stage, the objective function concerns the minimisation of the annualised total cost of the water supply system as provided by Eq. (5):

$$Min\ z_2 = \left[\underbrace{\frac{r.(1+r)^n}{(1+r)^n-1}.\left(CCDQ + CCSN + CCWT\right)}_{Annualised\quad Capital\quad Costs} + \overbrace{\sum_{t,i}\left(OCDQ_{t,i} + OCSN_{t,i} + OCWT_{t,i} + FOC_t\right)}^{Variable\quad and\quad Fixed\quad O\&M\quad Costs} \right] \tag{5}$$

In level-two objective function, the first term represents the annualised capital costs of the water supply system, calculated using capital recovery factor (CRF), $\frac{r.(1+r)^n}{(1+r)^n-1}$; where r (%) and n (y) are the weighted average cost of capital (WACC) and the project lifetime, respectively. The second term refers to O&M costs. Details of the capital and O&M costs at level-two optimisation are as follows:

- Capital costs of each component of the water supply system including desalination plants ($CCDQ$ (\$)), storage tanks ($CCSN$ (\$)), and pipelines ($CCWT$ (\$)) are given by Eqs. (6)-(8):

$$CCDQ = \sum_t \sum_i \sum_c CapDQ_c.XW_{t,i,c} \tag{6}$$

$$CCSN = \sum_t \sum_i \sum_m CapSN_m.X_{t,i,m} + \sum_t \sum_i \sum_j CapWT.YY_{t,i}.L_{i,j}.convf_2 \qquad \forall (i,j) \in \{L^{w}_{i,j} \mid i = j\} \tag{7}$$

$$CCWT = \sum_t \sum_i \sum_j CapWT.SY_{t,i,j}.L_{i,j}.convf_2 \qquad \forall (i,j) \in \{L^{w}_{i,j} \mid i \neq j\} \tag{8}$$

In Eq. (6), $XW_{t,i,c}$ is a binary variable, related to desalination plants design capacity. The binary variable of $X_{t,i,m}$ (Eq. (7)), corresponds to storage tanks size and the binary variable of $YY_{t,i}$ is associated with the pipeline from which extra desalinated water is transferred to the storage tank. The capital cost of the pipeline within zone i is calculated based on the distance from the desalination plant to the storage tank ($L_{i,j}$ (m) where $i = j$), and the conversion factor ($convf_2$ (km/m)). Eq. (8) determines the capital cost of the pipelines transferring desalinated water among allowable zones i and j. Here, the binary variable of

$SY_{t,i,j}$ represents the decision for installing a pipeline connecting zone i to j in planning horizon t.

- O&M costs of desalination plants ($OCDQ_{t,i}$ (\$)), water storage ($OCSN_{t,i}$ (\$)), and water transfer ($OCWT_{t,i}$ (\$)) are expressed by Eqs. (9)-(11):

$$OCDQ_{t,i} = \sum_s nd_s.\sum_b C^{eb}_{t,s,b}.P^{wDQ}_{t,i,s,b} + C^{rb}_t.RE^{wDQ}_{t,i,s,b} + C^{OM}_t.Q_{t,i,s,b} \qquad \forall t,i \tag{9}$$

$$CCSN_{t,i} = \sum_s nd_s.\sum_b C^{eb}_{t,s,b}.P^{wSN}_{t,i,s,b} + C^{rb}_t.RE^{wSN}_{t,i,s,b} + C^{s}_t.V_{t,i,s,b} \qquad \forall t,i \tag{10}$$

$$OCWT_{t,i} = \sum_s nd_s.\sum_b C^{eb}_{t,s,b}.P^{wWT}_{t,i,s,b} + C^{rb}_t.RE^{wWT}_{t,i,s,b} \qquad \forall t,i \tag{11}$$

In Eq. (9), $P^{wDQ}_{t,i,s,b}$ and $RE^{wDQ}_{t,i,s,b}$ (kWh) are, in order, the share of grid electricity and surplus PV output in meeting desalination plants electricity demand, and $Q_{t,i,s,b}$ (m^3) is the amount of desalinated water produced. In Eq. (10), $P^{wSN}_{t,i,s,b}$ is the share of grid electricity, and $RE^{wSN}_{t,i,s,b}$ (kWh) is the share of surplus PV output in supplying the electricity required for water storage. Here, $V_{t,i,s,b}$ (m^3) is the existing desalinated water in the storage tank. Lastly, in Eq. (11), $P^{wWT}_{t,i,s,b}$ and $RE^{wWT}_{t,i,s,b}$ (kWh) are grid electricity and surplus PV output, allocated to electricity demand of transferring water, respectively.

- Fixed costs associated with daily electricity charge for operation of the water supply system (FOC_t (\$)) is described according to Eq. (12):

$$FOC_t = \sum_s C^{feb}_t.nd_s \qquad \forall t \tag{12}$$

4.2.2. Water balance

In each zone and time period, the desalinated water assigned directly from the desalination plant ($WQ_{t,i,s,b}$ (m^3)) located in the same zone and the desalinated water assigned from the storage tank ($WV_{t,i,s,b}$ (m^3)), plus the transferred water from other zones ($WT_{t,j,i,s,b}$ (m^3)) need to fully satisfy water demand (Eq. (13)):

$$WQ_{t,i,s,b} + WV_{t,i,s,b} + \sum_{j:(i,j)\in\{L^w_{i,j} | i\neq j\}} WT_{t,j,i,s,b} = D^w_{t,i,s,b} \qquad \forall t,i,s,b \tag{13}$$

4.2.3. Desalination plants capacities

The design capacity of a desalination plant at zone i during planning horizon t ($DQ_{t,i}$ (m^3/day)) can be selected from c discrete values (Eq. (14)):

$$DQ_{t,i} = \sum_c AC_c.XW_{t,i,c} \qquad \forall t,i \tag{14}$$

The binary variable of $XW_{t,i,c}$ is only activated if the plant design capacity of AC_c (m^3/day) occurs in zone i during planning horizon t. Eq. (15) states that at most one desalination plant design capacity can occur in each zone during the planning horizon:

$$\sum_c XW_{t,i,c} \le 1 \quad \forall t,i \tag{15}$$

The upper bound of desalinated water production ($Q_{t,i,s,b}$ (m^3)) is expressed by Eq. (16):

$$\sum_s nd_s.\sum_b Q_{t,i,s,b} \le PF.\sum_s DQ_{t,i}.nd_s \quad \forall t,i \tag{16}$$

4.2.4. Storage tanks capacities

The size of a storage tank selected for zone i during the planning horizon t ($SN_{t,i}$ (m^3)) can be chosen from m discrete values (Eq. (17)):

$$SN_{t,i} = \sum_m ST_m.X_{t,i,m} \quad \forall t,i \tag{17}$$

Where the binary variable of $X_{t,i,m}$ is only activated if storage tank size of ST_m (m^3) occurs at zone i during planning horizon t.

Zone i can be only equipped with storage tank if a desalination plant (with any design capacity) is placed in the same zone (section 3). At the same time, at most one storage tank size can be selected for each zone during the planning horizon. Eq. (18) ensures both constraints as follows:

$$\sum_m X_{t,i,m} \le \sum_c XW_{t,i,c} \quad \forall t,i \tag{18}$$

The total capacities of storage tanks in the given area is constrained by minimum and maximum allowable stored water during the planning horizon (Eqs. (19)-(20)):

$$\sum_i SN_{t,i} \ge \sum_i MinS_{t,i} \quad \forall t \tag{19}$$

$$\sum_i SN_{t,i} \le \sum_i MaxS_{t,i} \quad \forall t \tag{20}$$

4.2.5. Water pushed from desalination plant towards storage tank

In each time period, the amount of desalinated water in zone i pushed for storage ($WTC_{t,i,s,b}$ (m^3)) equals to what remains after the amount assigned directly from desalination plant in zone i to meet the demand in the same zone ($WQ_{t,i,s,b}$ (m^3)) and the amount transferred from zone i to other zones ($WT_{t,i,j,s,b}$ (m^3)) (Eq. (21)). $WTC_{t,i,s,b}$ is also limited to the maximum capacity of the pipeline connecting the desalination plant to the storage tank within zone i (Eq. (22)):

$$WTC_{t,i,s,b} = Q_{t,i,s,b} - WQ_{t,i,s,b} - \sum_{j:(i,j)\in\{L^{w}_{i,j} | i\neq j\}} WT_{t,i,j,s,b} \qquad \forall t,i,s,b \tag{21}$$

$$WTC_{t,i,s,b} \leq convf_1.MaxTW_t.dur_b.YY_{t,i} \qquad \forall t,i,s,b \tag{22}$$

The binary variable of $YY_{t,i}$ is activated if a pipeline is chosen within zone i during planning horizon t, to transfer extra desalinated water from the desalination plant to the storage tank within the same zone.

There should be extra desalinated water production in zone i in order to place a pipeline. Hence, the selection of a pipeline for zone i needs to follow the occurrence of a storage tank (with any size) in the same zone (Eq. (23)):

$$YY_{t,i} \leq \sum_{m} XW_{t,i,m} \qquad \forall t,i \tag{23}$$

4.2.6. Desalinated water storage

In each time period, the existing desalinated water in the storage tank in zone i ($V_{t,i,s,b}$ (m^3)) is determined in terms of existing water in the storage tank from the previous time block ($V_{t,i,s,b-1}$ (m^3)) the amount pushed from the desalination plant towards the storage tank ($WTC_{t,i,s,b}$ (m^3)), and the amount assigned from the storage tank to meet the demand in the same zone ($WV_{t,i,s,b}$ (m^3))(Eq. (24)):

$$V_{t,i,s,b} = V_{t,i,s,b-1} + WTC_{t,i,s,b} - WV_{t,i,s,b} \qquad \forall t,i,s,b \tag{24}$$

In each time period, $V_{t,i,s,b}$ is limited to the size of the storage tank selected for zone i (Eq. (25)). Also, $WV_{t,i,s,b}$ cannot exceed the amount of existing desalinated water in the storage tank from the previous time block (Eq. (26)):

$$V_{t,i,s,b} \leq SN_{t,i} \qquad \forall t,i,s,b \tag{25}$$

$$WV_{t,i,s,b} \leq V_{t,i,s,b-1} \qquad \forall t,i,s,b \tag{26}$$

4.2.7. Water flows

In each time period, the maximum desalinated water that can be transferred from zone i to zone j ($WT_{t,i,j,s,b}$ (m^3)) is determined based on the maximum capacity of the connecting pipeline ($MaxTW_t$ (m^3/day))(Eq. (27)):

$$WT_{t,i,j,s,b} \leq convf_1.MaxTW_t.dur_b.Y_{t,i,j,s,b} \qquad \forall t,s,b,(i,j)\in\{L^{w}_{i,j} | i\neq j\} \tag{27}$$

The binary variable of $Y_{t,i,j,s,b}$ is activated if water transfer direction from zone i to j happens. Eq. (28) is defined to avoid the simultaneous reverse flow of water through the same pair of allowable zones and Eq. (29) guarantees that water transfer from zone i to other zones can only occur if it is equipped with a desalination plant (with any design capacity):

$$Y_{t,i,j,s,b} + Y_{t,j,i,s,b} \leq 1 \quad \forall t, s, b, (i, j) \in \{L^{w}_{i,j} | i \neq j\} \tag{28}$$

$$\sum_{j:(i,j)\in\{L^{w}_{i,j}|i\neq j\}} Y_{t,i,j,s,b} \leq U.\sum_{c} XW_{t,i,c} \quad \forall t, i, s, b \tag{29}$$

In which U is a big number.

A binary variable of $SY_{t,i,j}$ in Eq. (30) is defined to give decisions regarding the installation of pipeline connecting zone i to j and thus, this constraint ensures that water transfer from zone i to j can occur if only there is a pipeline in the final optimal solution.

$$SY_{t,i,j} \geq Y_{t,i,j,s,b} \quad \forall t, (i, j) \in \{L^{w}_{i,j} | i \neq j\} \tag{30}$$

4.2.8. Electricity balance

In each zone and time period, the electricity balance between electricity demand for households, which are not equipped with PV system ($(1-k_1).D^{er}_{t,i,s,b}$ (kWh)) and electricity sources is given by Eq. (31):

$$P^{rn}_{t,i,s,b} + RE^{rn}_{t,i,s,b} = (1-k_1).D^{er}_{t,i,s,b} \quad \forall t, i, s, b \tag{31}$$

Where $P^{rn}_{t,i,s,b}$ (kWh) represents the share of grid electricity and $RE^{rn}_{t,i,s,b}$ (kWh) is the share of surplus PV output in meeting the electricity demand.

For each zone and time period, Eqs. (32)-(34) present water-related electricity balance corresponding to water production, storage, and transfer, respectively:

$$P^{wDQ}_{t,i,s,b} + RE^{wDQ}_{t,i,s,b} = Q_{t,i,s,b}.D^{ep} \quad \forall t, i, s, b \tag{32}$$

$$P^{wSN}_{t,i,s,b} + RE^{wSN}_{t,i,s,b} = \sum_{j:(i,j)\in\{PL^{w}_{i,j}|i=j\}} WTC_{t,i,s,b}.D^{ewt}_{i,j} \quad \forall t, i, s, b \tag{33}$$

$$P^{wWT}_{t,i,s,b} + RE^{wWT}_{t,i,s,b} = \sum_{j:(i,j)\in\{PL^{w}_{i,j}|i\neq j\}} WT_{t,i,j,s,b}.D^{ewt}_{i,j} \quad \forall t, i, s, b \tag{34}$$

Therein, $PL^{w}_{i,j}$ is the subset of $L^{w}_{i,j}$ including allowable zones where pumping is needed for water transfer. In order to simplify, all above water-related electricity balance formula can be summarised as follows (Eq. (35)):

$$P^{w}_{t,i,s,b} + RE^{w}_{t,i,s,b} = TD^{ew}_{t,i,s,b} \quad \forall t,i,s,b \tag{35}$$

Where, $P^{w}_{t,i,s,b}$ (kWh) and $RE^{w}_{t,i,s,b}$ (kWh) are, in order, the share of grid electricity and surplus PV output in satisfying the electricity demand of all components of water supply system including production, storage, and transfer in each zone and time period ($TD^{ew}_{t,i,s,b}$ (kWh)).

4.2.9. Energy resources capacities

In each zone and time period, the share of grid electricity in meeting the total electricity demand (both residential and water supply system) is limited to the maximum capacity of associated zone substations (Eq. (36)). Moreover, the share of renewable energy in supplying the electricity demand cannot exceed the available surplus PV output (Eq. (37)).

$$P^{rn}_{t,i,s,b} + P^{w}_{t,i,s,b} + PP^{r}_{t,i,s,b} \le dur_b .MaxPS_{t,i} \quad \forall t,i,s,b \tag{36}$$

$$RE^{rn}_{t,i,s,b} + RE^{w}_{t,i,s,b} \le Surp_{t,i,s,b} \quad \forall t,i,s,b \tag{37}$$

5. Perth, Western Australia: background and description of scenarios

The optimisation model was applied to an urban area located in the north-western corridor of Perth, WA, the largest desalinated water consumer in Australia [27]. Currently, 47% of water demand in Perth and surroundings is met by two large Southern and Perth desalination plants [28]. Due to rapid urbanisation and population growth in this part of the city and given the adverse impact of climate change on groundwater resources, it has been suggested that up to 100 GL/y of the future water demand in this area will be supplied by desalinated water [29].

In this study, however, it is assumed the total water demand in the studied area is only met by desalinated water and therefore, the existing water supply system wasnot taken into account. The optimal investment options and operational scheduling of a desalination-based water supply system for the given area was evaluated through three scenarios of *fixed*, *semi-flexible* and *flexible*, named based on operational scheduling of desalination plants for the planning horizon of one year[1].

In *fixed* scenario, selected desalination plants need to be operated at their full capacity to produce a fixed amount of water for all hours of a day throughout the year. This is a common operational scheduling currently implemented in many desalination plants such as Southern and Perth desalination plants. In *semi-flexible* scenario, it is assumed that the amount of water produced can vary on seasonal basis while it still needs to remain constant during all hours of a day. This means that a desalination plant can operate in different fractions of its full capacity on seasonal basis. The relatively similar example of this operational scheduling is “hot standby” mode of operation, where a desalination plant works with different capacities in various time-periods [30]. Table A.1 in supplementary document presents the operational capacities of each plant design capacity considered in this study for *semi-flexible* scenario. Lastly, in *flexible* scenario, the amount of water produced daily can vary on hourly basis, which potentially can provide the most compatibility with

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[1] All data collected is for the time of research, 2016

the intermittent and hourly variation of the available surplus PV output. It is notable that the water production of a desalination plant defined in equations of section 4 are related to *flexible* scenario. Eqs. (A.1)-(A.7) in supplementary document define this variable and associated equations for *semi-flexible* and *fixed* scenarios based on their specific constraints.

It should be mentioned that the data collected for this study is composed of sets with continuous values such as distance and pumping elevation between allowable zones, and sets with discrete values like the capacities of water and energy supply components as well as hourly water and energy demands, maximum possible PV output and electricity cost tariffs. The temporal datasets were determined for each zone and time period (considering 4 zones within the case study, each set contains 384 data).The following sections describe different characteristics of water and energy demand and supply system and associated costs for the case-study in more details. It is notable that where the real data was not available, the data was estimated or adopted based on valid references.

5.1. Water demand and supply system

Using ArcGIS 10, the case study is divided into four zones. The boundaries of each zone were determined based on local government area (LGA) and associated population data [31] as well as the service area of the existing distribution substations in the studied area, obtained from Western Power, main WA's electricity supplier. To determine water demand in each zone, a simple unit loading method [32] was applied. In this method, water demand is defined as the product of the unit demand and the number of the customers. Constant distribution of water demand was also presumed throughout the year, resulting in the constant hourly water demand. Thus, considering the annual water demand of 126 m^3 per capita [33], the hourly water demand achieved was equal to 0.014 m^3 per capita.

As mentioned in section 5, the whole water demand in the case study area is fulfilled through desalination-based water supply system consisting of seawater reverse osmosis (SWRO) desalination plants, storage tanks, and a pipeline network. Different desalination plants design capacities and storage tanks sizes from which the optimal solution can be selected are tabulated in Table 1. The plant factor of 0.85 was considered to specify the full capacity of water production for each desalination plant design capacity [34]. The maximum and minimum allowable stored water were also determined such that it can cover at least 2 hours and maximum 1 day of water demand in the case-study area. No stored water was considered at the beginning of the planning horizon.

The size of 48 in. diameter pipe was considered for installation of any connecting pipeline in the studied area and the associated capacity was calculated based on water velocity of 0.8 m/s. Water can only be transferred within a zone between desalination plant and storage tank or among adjacent (allowable) zones. Table 2 summarises the distance and elevation differences within/among zones for water transfer.

In addition, the suitable locations for the potential water infrastructures in each zone was determined using the layer of imagery base map in GIS. Fig. 2 indicates zone boundaries, possible locations for sitting potential water supply system components and spatial distribution of average annual water demand.

5.2. Energy demand and supply system

In this study, energy demand is associated with households and a water supply system. For each time period, residential electricity demand was determined by means of the index of the average annual hourly electricity consumption per capita. Considering 2.6 people per household [35], this index was calculated based on the substations' annual hourly electricity data in the case-study area and the number of total connected households to the electrical grid. The substations' data was obtained from Western Power. Fig. 3 depicts an average seasonal hourly profile of residential electricity consumption in the studied area.

Water production and transfer are the main energy consumers in a desalination-based water supply system. The average specific energy consumption of 4 kWh/m^3 was considered for all desalination plants capacities based on Ref. [36]. The specific energy consumption for water transfer within a zone or among adjacent zones was obtained based on the assumptions of our previous study [26].

The electricity demand in the area is mainly supplied by fossil fuel-based power plants through electrical grid. At distribution level, 16 substations deliver grid electricity to the studied area [37]. In this study, the maximum capacity of each zone substations is estimated in terms of their transformers' ratings as explained in Ref. [38]. The data associated with transformers and their power factor was adopted from Ref. [39]. The maximum estimated capacities of zone substations are presented in Table 3.

Another source of energy supplying a part of the required electricity demand is residential grid-connected rooftop PVs. These systems have been installed behind the meter meaning that the PV output is only fed to the electrical grid after the residential usage. Currently, the total capacity of 118.5 MW [40] has been installed in the case-study area. It is assumed that current commonly used 4 kW PV system [41] is the only system size installed in the area. Using SAM 2016.3.14 [42], the performance of a single PV system for 8760 hours of a year were determined.The main input data for SAM model are tabulated in Table 4.

For the calculation of the maximum possible PV systems output, the same PV installation density of 23% was considered for each zone within the studied area. Using trial and error, this value was achieved such that no unused surplus electricity remains after meeting both residential and water-related electricity demand in each time period. Fig. 4 presents the maximum annual hourly PV systems output calculated for each zone. It is notable that the similar PV systems output in Z2 and Z3 is associated with relatively the same number of households in these two zones.

5.3. Cost data

All cost data associated with grid electricity and surplus PV output usage as well as water supply system components' capital and operational costs were adopted from the literature and adjusted to 2016 Australian dollars ($) using the related exchange rate according to [44].

The electricity rates were determined based on the residential and business TOU electricity tariffs as well as the net FiT electricity rate ($ 0.07135/kWh), obtained from Refs. [45, 46]. In fact, the electricity cost not only depends on the amount of electricity consumption but also the energy source (grid electricity or PV output) assigned to the demand. Therefore, the electricity cost of different water supply systems including desalination plants, storage tanks and pipelines was calculated directly by the optimisation model taking into account associated electricity tariff prices. Fig. 5 shows the residential and business TOU electricity tariffs implemented in the case-study.

Apart from electricity cost, other components of the O&M costs as well as capital costs for different desalination plants capacities were estimated based on Refs. [34, 47] and for storage tanks sizes were calculated according to Refs. [48, 49]. Accordingly, the model input data for average O&M cost per unit of water produced and stored were determined \$0.363 /m^3 and \$0.127 /m^3, respectively. The breakdown of the capital and O&M costs of different design capacities of desalination plants and storage tanks sizes are presented in Tables A.2 & A.3 of the supplementary document.

The unit-installed cost of the pipeline was also considered \$1,822,986 based on Ref. [50]. The operational cost of transferring water within a zone or among adjacent zones was calculated based on the electricity cost of water pumping.

Lastly, for calculations of the annualised total cost of water supply system the real WACC of 4.03% was adopted from Ref. [51] and the lifetime of the project was considered to be 20 years.

6. Results and discussion

The two-level MILP optimisation problem was implemented in GAMS 24.3.1 and solved for different scenarios to a relative optimality criterion of 0.1%, using solver CPLEX 12.6 [52] As seen in Table 5, the size of the model in different scenarios is not changed significantly and the optimal solutions are found in less than a minute. In fact, the two-level optimisation formulation approach was primarily chosen based on the nature of the described problem. However, it had the secondary advantage of reducing the complexity of the model. Accordingly, along with the selected timeframe (as mentioned in section 3), the optimal solutions for all three scenarios can be found in a short elapsed time.

The last column of Table 5 indicates the relative optimality gap for each scenario. It is notable that the problem is solved to the optimality in *fixed* scenario, and in two other scenarios, the optimal solutions satisfy the selected relative optimality criterion. This suggests that CPLEX produces strong bounds for optimal integer solution.

6.1. Comparison of three system operational scheduling

The optimum solution for three scenarios of *fixed*, *semi-flexible* and *flexible* leads to annualised total costs of \$ 163 300 398, \$ 154 148 278 and \$ 144 626 853, respectively. Fig. 6 depicts the breakdown of the optimal annualised total cost for three operational scheduling. As shown, water production has the highest contribution in the annualised total cost of the system in all scenarios (more than 85%) followed by water storage and then water transfer. It should be mentioned that the annual fixed costs associated with daily electricity charge for operation of the water supply system is negligible compared to other expenses (around \$3760) and therefore it is not demonstrable in Fig. 6.

6.1.1. Optimal investment decisions of desalination-based water supply system

Table 6 summarises the details of the optimal investment options of the water supply system components as well as the annual desalinated water production in three scenarios.

The optimal solution for *fixed* and *flexible* scenarios results in two desalination plants and storage tanks in zones, 2 and 4 with similar capacities. However, the model considers the larger storage tank size in zone 2 and the smaller storage tank size in zone 4 for *fixed* scenario as opposed to *flexible* scenario. In *fixed* scenario, the production of water in all hours of the day throughout a year remains constant, leading to about 28% more water production in zone 2 compared to *flexible* operational scheduling (Table 6). Thus, even after supplying the total demand in zone 2 and transferring water to zones 1 and 3, there is still a large amount of water remains unused and therefore needs to be stored. Hence, the larger tank size has been chosen in this zone as compared to *flexible* scenario. In zone 4, the same amount of water is produced in both scenarios and selection of the larger tank size in *flexible* scenario, is the result of the constraint considered for the minimum capacity of the total storage tanks in the studied area which needs to be able to cover at least 2-hour total demand. In these two scenarios, the annualised capital cost of water supply system are similar. However, the annual operational costs in *fixed* scenario is \$18 673 545 more compared to *flexible* scenario. This is partly due to the higher share of surplus PV output in *flexible* scenario (38%) in meeting the demand (Fig. 7) which offsets the costs of water production during peak hours corresponding to high electricity rate. The other reason is related to the less water production and hence water storage and transfer (within a zone) in this scenario leading to less electricity consumption and therefore, annual operational costs.

In *semi-flexible* scenario, three zones of 1, 2 and 4 are equipped with desalination plants and associated storage tanks. The annualised capital cost of optimal water supply system is higher than the other two scenarios, namely \$1 060 383 reflecting the absence of economies of scale of smaller desalination plants in this scenario. As shown in Fig. 7, the contribution of the surplus PV output to supply water-related energy demand is relatively similar in *semi-flexible* and *fixed* scenarios, accounting for about 30% of the total demand. Despite this, the seasonal flexibility of the water production in *semi-flexible* scenario leads to \$10 212 503 less annual operational cost compared to *fixed* scenario. However, when it comes to *flexible* scenario, *semi-flexible* scenario by far results in higher annual operational cost of the optimal water supply system (around \$8 461 042), associated with the amount of water produced and hence needs to be stored and transferred.

6.1.2. Optimal operation scheduling of desalination-based water supply system

Since in each scenario, the logic behind the optimal solution is similar for all zones and seasons, in this section, only the optimal daily operational scheduling of the desalinated-based water supply system during summer for the representative zone 2 is described (Figs. 8-10). Tables A.4-A.12 in the supplementary document include the details of the optimal solution in summer for all zones within the case study.

The general operational scheduling of water supply and the paradigm of surplus PV output usage for water-related energy supply in *fixed* scenario is the same as *semi-flexible* scenario (Figs. 8-10a vs. 8-10b). The reason mainly relates to the fact that in both scenarios there is no flexibility in the level of water production during a day. However, since in *fixed* scenario the selected desalination plants need to be operated full capacity all year long, they naturally produce higher volume of water each day. As a result, compared to *semi-flexible* scenario, the larger portion of the produced water is pushed towards the storage tank (19.61% vs 5.9%) (Figs. 9a and 9b). In this scenario, 26.19% of the total water-related electricity demand in zone 2 is provided by surplus PV output (Fig. 10a), resulting in total \$1 851 596 O&M cost savings for water supply in summer. It is notable that, despite this apparent savings, the annualised total cost of the water supply system in this scenario is higher than the other scenarios (as mentioned earlier in section 6.1.1). In other words, using renewable energy cannot compensate the extra costs caused by high level of desalinated water production.

In *semi-flexible* scenario, the desalination plant capacity of 40000 m^3/day is chosen for zone 2, which can be operated in different capacity fractions only on seasonal basis. In this scenario, 100% of the water demand is satisfied by desalinated water distributed directly from the plant (Fig. 8b) and the overall water transfers including the amount of water pushed towards the storage tank is minimised (Fig. 9b). In this scenario, during each season, the production of water in all hours of the day remains constant; Thus the model can only minimise the costs associated with water storage and transfer in order to decrease the annualised total cost of the system.

Additionally, while the model assigns the surplus PV output for meeting the electricity demand when plausible (Fig. 10b), due to non-flexibility of the operational approach, it cannot fully benefit from this source of energy to reduce the cost of the water supply during peak electricity rate. In this scenario, about 29.1% of the water-related energy demand in zone 2 is supplied by surplus PV output corresponding to total $1 354 571 O&M cost savings for water supply in this season.

In *flexible* scenario, the desalination plant capacity of 60000 m^3/day is located in zone 2. As shown in Fig. 8c, around 82% of the demand in this zone is provided by the desalinated water distributed directly from the plant. In addition, during the peak electricity hours when surplus PV output is not available, existing stored water is the priority to meet water demand. It is notable that as opposed to two other scenarios in which water is pushed for storage mainly due to the extra water production, in flexible scenario, this happens only during the availability of surplus PV output (Fig. 9c and 10c).

From energy point of view, except for when it is not available, water-related energy demand is satisfied by surplus PV output (Fig. 10c). In this scenario, due to the possibility of optimising the system operation on hourly basis, it is economically beneficial to produce higher volume of water during the hours when renewable energy is available and push the extra amount to the storage (Figs. 9c and 10c). As a result, the highest water-related energy demand associated with desalinated water production, occurs during the availability of the renewable energy, even though it is coincident with the peak electricity rate hours. In this scenario, 40.1% of the total water-related energy demand in zone 2 is met by surplus PV output resulting in total $2 124 291 O&M cost savings for water supply in summer.

6.1.3. The effect of seasonal changes on optimal operation of desalination-based water supply system

Figs. 11 and 12 indicate the optimal operation of desalination-based water supply system from both water and energy points of view in different seasons and for all zones. The seasonal changes do not show a significant effect on the optimal operation of the system to deliver water demand in any of the scenarios (Fig. 11). This is the result of the hourly water demand per capita assumed to be constant throughout the year. Alternatively, the impact of seasonal changes is mainly on the share of different energy sources in providing water-related electricity demand (Fig. 12). This effect corresponds to the fluctuations of available surplus PV output due to the seasonal variation of solar radiation, residential electricity usage profile as well as the flexibility of the system in each operational scheduling in adjusting to the available renewable energy source. Accordingly, the maximum and minimum share of the surplus PV output in supplying total water-related energy demand occurs in summer and winter, equal to 35.7% and 20.1% in *fixed* scenario, 37% and 21.8% in *semi-flexible* scenario and 46.1% and 26.5% in *flexible* scenario, respectively.

6.2. Optimal solutions in three operational scenarios versus Southern seawater desalination plant

This study aims at investigating different possibilities of an optimal desalination-based water supply system driven by grid electricity and surplus PV output for north-western suburbs of Perth, where constructing a new desalination plant for their future demand has been suggested (section 5). However, in order to compare the optimal results achieved for three scenarios with the real-world case, centralised Southern seawater desalination plant has been chosen which contributes around one third of water supply in Perth and has the production capacity of 100 GL/y [53]. The SWRO desalination plant is operated at its full capacity, and produces a fixed amount of water all hours of a day throughout the year and uses grid electricity as its energy source. However, the equivalent amount of electricity demand of the plant is purchased from solar and wind farms on yearly basis for sustainability purposes [53].

Considering that Southern seawater desalination plant is a part of existing Perth's water supply system and the amount allocated from this plant to the case-study area is not traceable, the annualised unit cost of water production has been selected as a metric for comparison. Therefore, in order to make a relatively uniform platform for comparison, only the annualised unit cost of water production in each scenario has been considered in this comparison and water storage and transfer have not been taken into account. Table 7 summarises the economic performance of optimal solutions versus Southern seawater desalination plant.

As shown in Table 7, compared to Southern seawater desalination plant, *flexible* scenario has the highest economic benefit, namely 19.9%, followed by *fixed* (16.3%) and then *semi-flexible* (13.7%) scenarios in terms of annualised unit cost of water production. It is worth mentioning that although the annualised total cost of water production in *fixed* scenario is higher than *semi-flexible* scenario (around $3 218 085), the higher level of water production leads to the less annualised unit cost in this scenario.

6.3. Sensitivity analysis

In this study, the sensitivity of the annualised unit cost of water supply in three operational scenarios has been investigated by changing the assumptions regarding PV installation density and WACC.

As mentioned in section 5.2, in this study, the PV installation density of 23% is assumed in each zone within the case-study boundary. This is the maximum level of PV installation density which results in using all surplus PV output in the studies area after meeting all the demands. In order to evaluate the impact of different PV installation density on the annualised unit cost of water supply, two other cases have been analysed when there is no PV installation (installation density of 0%) and when only around half of the assumed PV installation occurs (installation density of 10%). The optimal solution for both cases was then obtained in each of the three scenarios (Fig. 13a).

In addition, in the reference scenarios, the cost analysis has been conducted considering the real WACC of 4.03%. As a sensitivity test, two other rates were taken into account, namely 5.63% and 6.62% proposed by Economic Regulation Authority (ERA) in their earlier reports [51]. The results of the sensitivity analysis for both cases and in each scenario are presented in Fig. 13b.

In summary, the results indicate high resilience to changes in the WACC rate, while it shows relatively high sensitivity to the installation density. Accordingly, the economic benefit of the system with the installation density of 23% over 0% in terms of the annualised total cost of the water supply equals to \$27 114 845 in *fixed* scenario, \$27 027 864 in *semi-flexible* scenario and \$27 784 872 in *flexible* scenario. Similarly, compared to the installation density of 10%, the economic benefit of the installation density of 23% in *fixed*, *semi-flexible*, and *flexible* scenarios is \$8 642 407, \$7 884 552, and \$10 036 514, respectively. High economic benefits of the system in the presence of the renewable energy compared to lack of this source of energy shows the importance of implementing the policies facilitating higher PV installations in the studied area.

7. Conclusion

In this paper, an optimisation model was proposed for investment decisions and operational scheduling of a desalination-based water supply system integrated with small-scale rooftop PVs. The two-level MILP model determined the optimal size and location of different water supply system components as well as the schedule of the water production, storage, and transfer. The model was applied to an urban area located in the north-western corridor of Perth and solved for three water supply system operational scenarios of *fixed*, *semi-flexible*, and *flexible*. The results suggested that for a given year, the *flexible* scenario has \$9 521 425 and \$18 673 545 economic benefit compared to *semi-flexible* and *fixed* scenarios, respectively. Also higher share of available surplus PV output for water-related electricity demand was achieved in *flexible* scenario (38%) compared to *semi-flexible* (31%) and *fixed* (29%) scenarios suggesting the highest compatibility of this operational scheduling with available surplus PV output.

In addition, the optimal solutions were compared to Southern seawater desalination plant in Perth in terms of annualised unit cost of water produced. The results showed the significant economic benefit in *flexible* scenario (19.9%) and then *fixed* (16.3%) and *semi-flexible* (13.7%) scenarios over the existing desalination plant. Although there is still a lack of enough confidence in industry section to operate water supply systems in real-time fashion, the results of this study implies that it is worthwhile to look into this type of operational scheduling as a promising option, especially when there is the availability of the renewable energy which can be consumed at the time of generation.

The impact of seasonal changes on the operation of the water supply system in each scenario as well as its impact on the contribution of each energy resource to meet the water-related energy demand were also investigated. The results showed a negligible change in the optimal operation of water supply with seasonal variation as a result of assuming constant hourly water demand per capita throughout the year. However, renewable energy has higher share in meeting the water-related energy demand in summer time namely 35.7%, 37% and 46.1% as opposed to 20.1%, 21.8% and 26.5% in winter time, in *fixed*, *semi-flexible* and *flexible* scenarios, respectively. This is due to seasonal variation in available solar radiation and the flexibility of the system operation in adjusting to this source of energy.

Lastly, the sensitivity of the annualised unit cost of optimal water supply system with three different PV installation densities and rates of weighted average cost of capital was evaluated. The sensitivity of the results to PV installation density was shown to be higher than the sensitivity to financial rate in all scenarios, suggesting the importance of developing policies such as incentive programs to increase PV installation density in the case study area.

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Nomenclature

Sets

b	time block
c	set of discrete points of desalination plants design capacity
f	set of discrete points of desalination plants operational capacity fraction (used in *semi-flexible* scenario)
i, j	zone
$L^{w}_{i,j}$	allowable zones (i, j) for water transfer
m	set of discrete points of storage tanks size
$PL^{w}_{i,j}$	allowable zones (i, j) for water transfer where pumping is needed
s	season
t	planning horizon

Parameters

AC_{c}	design capacity of desalination plant at capacity breakpoint c (m^3/day)
$C^{eb}_{t,s,b}$	variable electricity charge for business sector per unit of grid electricity usage in planning horizon t season s and time block b ($/kWh)
$C^{er}_{t,s,b}$	variable electricity charge for residential sector per unit of grid electricity usage in planning horizon t season s and time block b ($/kWh)
C^{rb}_{t}	variable electricity charge for business sector per unit of renewable energy usage in planning horizon t ($/kWh)
C^{feb}_{t}	fixed daily electricity charge for business sector in planning horizon t ($/day)
C^{fer}_{t}	fixed daily electricity charge for residential sector in planning horizon t ($/day)
C^{OM}_{t}	average desalination plants O&M cost per unit of water production in planning horizon t ($/m^3)
C^{s}_{t}	average O&M cost per unit of stored desalinated water in planning horizon t ($/m^3)
$CapDQ_{c}$	capital cost of the desalination plant at capacity breakpoint c ($)
$CapSN_{m}$	capital cost of storage tank at size breakpoint m ($)
$CapWT$	capital cost per unit length of pipeline ($/km)
$convf_{1}$	conversion factor (day/h)
$convf_{2}$	conversion factor (km/m)
$D^{er}_{t,i,s,b}$	residential energy demand in zone i during planning horizon t season s and time block b (kWh)
$D^{w}_{t,i,s,b}$	water demand in zone i during planning horizon t season s and time block b (m^3)
D^{ep}	electricity demand per unit of water produced (kWh/m^3)
$D^{ewt}_{i,j}$	electricity demand per unit of water transferred within zone i or from zone i to j (kWh/m^3)
dur_{b}	duration of the time block b (h)
k_{1}	PV installation density (%)
$L_{i,j}$	distance from desalination plant to storage tank within zone i or from desalination plant in zone i to demand centre in zone j (m)
$MaxPS_{t,i}$	maximum capacity of substations in zone i during planning horizon t (kW)
$MaxR_{t,i,s,b}$	maximum possible PV output correspondent to installation density k_{1} in zone i during planning horizon t season s and time block b (kWh)
$MaxS_{t,i}$	maximum allowable stored water (m^3)
$MaxTW_{t}$	maximum pipeline capacity in planning horizon t (m^3/day)
$MinS_{t,i}$	minimum allowable stored water (m^3)
n	project lifetime (y)
nd_{s}	number of days in each season (day)
PF	plant factor
$PP^{r}_{t,i,s,b}$	auxiliary parameter of level-one optimisation (kWh)
$PQ_{c,f}$	operational capacity of a desalination plant at design

	capacity breakpoint c and operational capacity fraction breakpoint f (m^3/day) (used in *semi-flexible* scenario)
r	weighted average cost of capital (WACC) (%)
ST_m	size of storage tank at size breakpoint m (m^3)
$Surp_{t,i,s,b}$	auxiliary parameter of level-one optimisation (kWh)
U	a big number

Continuous variables

$CCDQ$	capital cost of desalination plants ($)
$CCSN$	capital cost of storage tanks ($)
$CCWT$	capital cost of pipelines ($)
$DQ_{t,i}$	design capacity of the desalination plant in zone i during planning horizon t (m^3/day)
FOC_t	fixed electricity charge for operating water supply system in planning horizon t ($)
$OCDQ_{t,i}$	O&M cost of desalination plants in zone i during planning horizon t ($)
$OCSN_{t,i}$	O&M cost of water storage in zone i during planning horizon t ($)
$OCWT_{t,i}$	O&M cost of water transfer in zone i during planning horizon t ($)
$P^{r}_{t,i,s,b}$	share of grid electricity to meet electricity demand of households equipped with PV system in zone i during planning horizon t in season s and time block b (kWh)
$P^{rn}_{t,i,s,b}$	share of grid electricity to meet electricity demand of households not equipped with PV system in zone i during planning horizon t in season s and time block b (kWh)
$P^{w}_{t,i,s,b}$	total share of grid electricity to meet water-related electricity demand in zone i during planning horizon t in season s and time block b (kWh)
$P^{wDQ}_{t,i,s,b}$	share of grid electricity to meet desalination plants electricity demand in zone i during planning horizon t in season s and time block b (kWh)
$P^{wSN}_{t,i,s,b}$	share of grid electricity to meet electricity demand of water storage in zone i during planning horizon t in season s and time block b (kWh)
$P^{wWT}_{t,i,s,b}$	share of grid electricity to meet electricity demand of water transfer from zone i during planning horizon t in season s and time block b (kWh)
$Q_{t,i,s,b}$	desalinated water produced in zone i during planning horizon t in season s and time bock b (m^3)
$Q_{t,i,s}$	daily desalinated water produced in zone i during planning horizon t in season s (m^3/day) (used in *fixed* and *semi-flexible* scenarios)
$RE^{r}_{t,i,s,b}$	share of PV output to meet electricity demand of households equipped with PV system in zone i during planning horizon t in season s and time block b (kWh)
$RE^{rn}_{t,i,s,b}$	share of surplus PV output to meet electricity demand of households not equipped with PV system in zone i during planning horizon t in season s and time block b (kWh)
$RE^{w}_{t,i,s,b}$	total share of surplus PV output to meet water-related electricity demand in zone i during planning horizon t in season s and time block b (kWh)
$RE^{wDQ}_{t,i,s,b}$	share of surplus PV output to meet desalination plants electricity demand in zone i during planning horizon t in season s and time block b (kWh)
$RE^{wSN}_{t,i,s,b}$	share of surplus PV output to meet electricity demand

	of water storage in zone i during planning horizon t in season s and time block b (kWh)
$RE^{wWT}_{t,i,s,b}$	share of surplus PV output to meet electricity demand of water transfer from zone i during planning horizon t in season s and time block b (kWh)
$SN_{t,i}$	size of the storage tank in zone i during planning horizon t (m^3)
$TD^{ew}_{t,i,s,b}$	total water-related energy demand in zone i during planning horizon t in season s and time block b (kWh)
$V_{t,i,s,b}$	existing desalinated water stored in the storage tank in zone i during planning horizon t in season s and time block b (m^3)
$WQ_{t,i,s,b}$	desalinated water assigned directly from desalination plant in zone i to meet water demand in the same zone during planning horizon t in season s and time block b (m^3)
$WT_{t,i,j,s,b}$	desalinated water transferred from zone i to j during planning horizon t in season s and time block b (m^3)
$WTC_{t,i,s,b}$	water pushed for storage from desalination plant in zone i during planning horizon t in season s and time block b (m^3)
$WV_{t,i,s,b}$	desalinated water assigned from storage tank in zone i to meet water demand in the same zone during planning horizon t in season s and time block b (m^3)

Binary variables

$SY_{t,i,j}$	1 if a pipeline connecting zone i to j occurs during planning horizon t; 0 otherwise
$X_{t,i,m}$	1 if the storage tank at size breakpoint m occurs in zone i during planning horizon t; 0 otherwise
$XK_{t,i,s,c,f}$	1 if for the desalination plant at design capacity breakpoint c, the operational capacity fraction breakpoint f occurs in zone i during planning horizon t in season s; 0 otherwise (used in *semi-flexible* scenario)
$XW_{t,i,c}$	1 if the desalination plant at design capacity breakpoint c occurs in zone i during planning horizon t; 0 otherwise
$Y_{t,i,j,s,b}$	1 if water transfer direction from zone i to j occurs during planning horizon t in season s and time block b; 0 otherwise
$YY_{t,i}$	1 if a pipeline is placed in zone i during planning horizon t, to transfer extra desalinated water from the desalination plant in zone i to the storage tank within the same zone; 0 otherwise

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Water supply component	Size
Desalination plant (m^3/day)	20000
	40000
	60000
	80000
	100000
	120000
	140000
Storage tank (m^3)	5000
	10000
	20000

Table 1- Desalination plants design capacities and storage tanks sizes

	Distance/pumping elevation (m)			
	Z1	Z2	Z3	Z4
Z1	4451/8.91	10922/-	-	-
Z2	13602/27.99	3073/2.94	16787/9.79	-
Z3	-	17955/1.76	8894/8.61	14572/13.52
Z4	-	-	16835/3.97	8882/8.88

Table 2- Distance and pumping elevation within a zone and between adjacent (allowable) zones (Z)

	Z1	Z2	Z3	Z4
Zone substations capacity (kW)	76000	152000	190000	494000

Table 3- Estimated maximum capacities of zone substations in the studied area

Data group	Description
Weather file data	Australia AUS Perth (INTL), obtained from SAM solar resource library
System components	
Solar panel module technical specification	Hanwha Solar HSL 60 S POLY
Inverter power technical specification	Fronius Primo
System design and configuration	
Total module area (m^2)	26.7
Number of subarrays	2
Tilt (degree)	22.6 [43]
Azimuth (degree)-subarray 1	300 based on [43]
Azimuth (degree)-subarray 2	60 based on [43]

Table 4- SAM model input data

Scenario	No. of Constraints	No. of total variables	No. of continuous variables	No. of binary variables	No. of iterations	Elapsed time (s)	Relative optimality gap (%)
Fixed	12943	10083	9457	626	13660	11	-[1]
Semi-flexible	13059	10531	9457	1074	33514	18	1.17E-08
Flexible	12931	10451	9825	626	104341	44	4.08E-02

[1] The problem was solved to the optimality

Table 5- The model statistics for each scenario

	Fixed	*Semi-flexible*	*Flexible*
Annualised unit cost of water supply[1] (\$/m^3) and relative difference with *flexible* scenario	2.63/5.62%	2.62/5.22%	2.49/0%
Annual economic benefit of *flexible* scenario over other operational scheduling (\$)	18 673 545	9 521 425	-
Desalination plant location/ design capacity (m^3/day)	Z2(60000) Z4(140000)	Z1(20000) Z2(40000) Z4(140000)	Z2(60000) Z4(140000)
Annual desalinated water production[2] (m^3)	Z2(18615000) Z4(43435000)	Z1(3102500) Z2(12410000) Z4(43435000)	Z2(14587010) Z4(43435000)
Storage location/ capacity (m^3)	Z2(10000) Z4(5000)	Z1(5000) Z2(5000) Z4(5000)	Z2(5000) Z4(10000)
Pipeline (links)	Z2-Z1 Z2-Z3 Z4-Z3	Z2-Z3 Z4-Z3	Z2-Z1 Z2-Z3 Z4-Z3

[1] This economic metric has been calculated considering all components of the desalination –based water supply system including production, storage and distribution

[2] Given the plant factor of 0.85

Table 6- Details of the optimal solution for water supply system in three scenarios

	Southern seawater desalination plant	*Fixed*	*Semi-flexible*	*Flexible*
Annualised unit cost of water production (\$/m^3) and relative difference over Southern seawater desalination plant	2.77[1] [54]	2.32/16.3%	2.39/13.7%	2.22/19.9%

[1] After converting to 2016 Australian dollar

Table 7- Comparison of optimal results with Southern seawater desalination plant in Perth

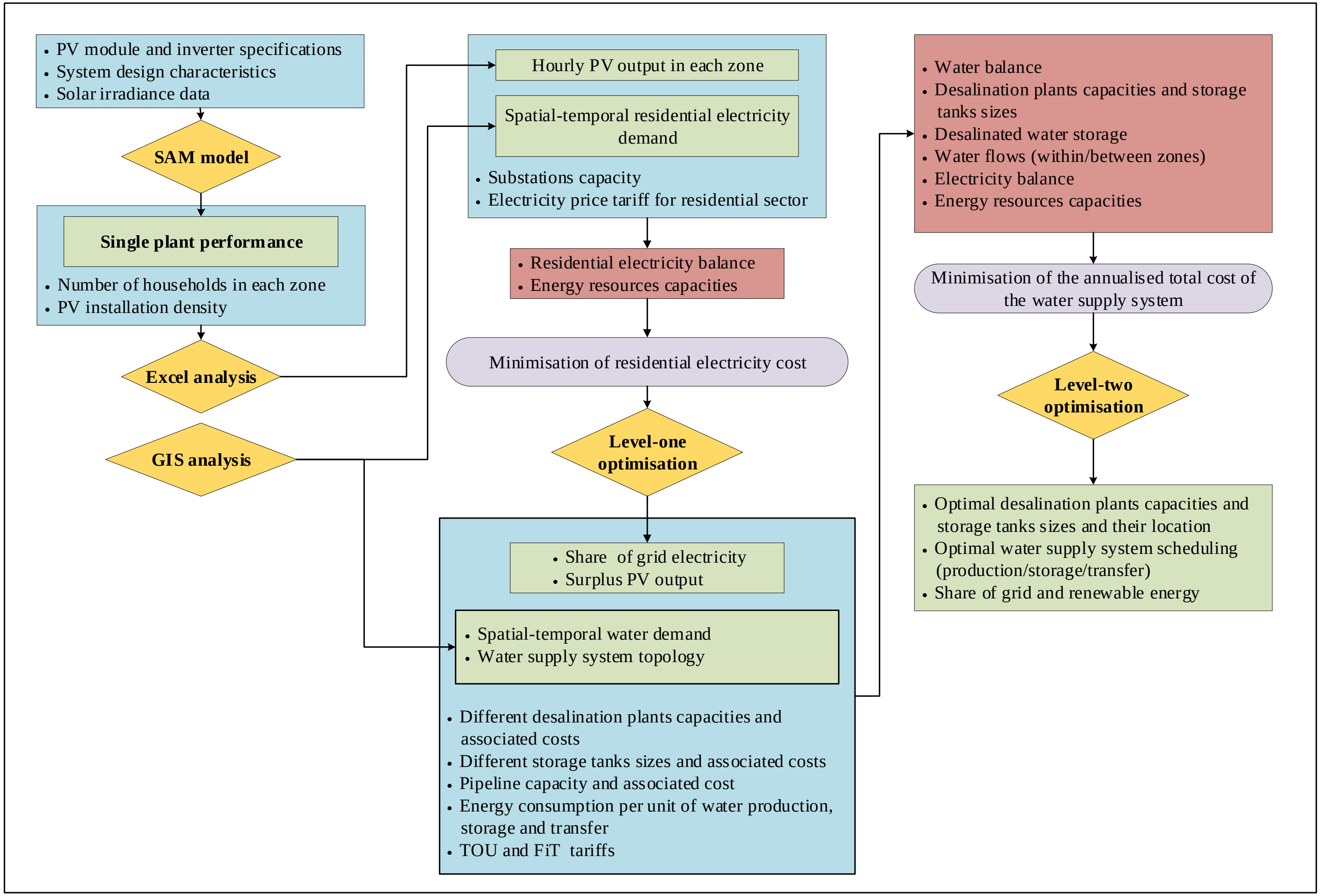

Fig. 1- Depiction of proposed two-level optimisation model

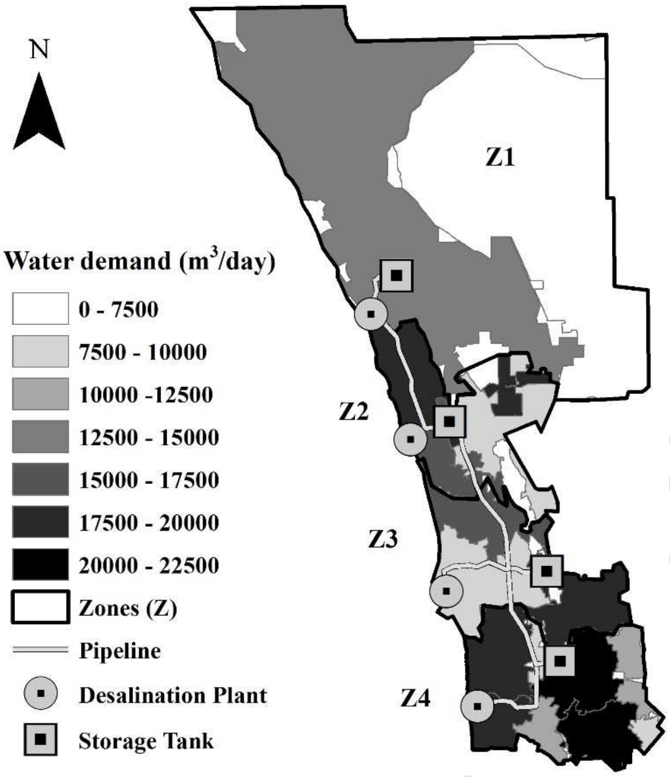

Fig. 2- Zones boundaries, possible locations for potential desalination plants, storage tanks and connecting pipelines, as well as spatial distribution of average annual water demand

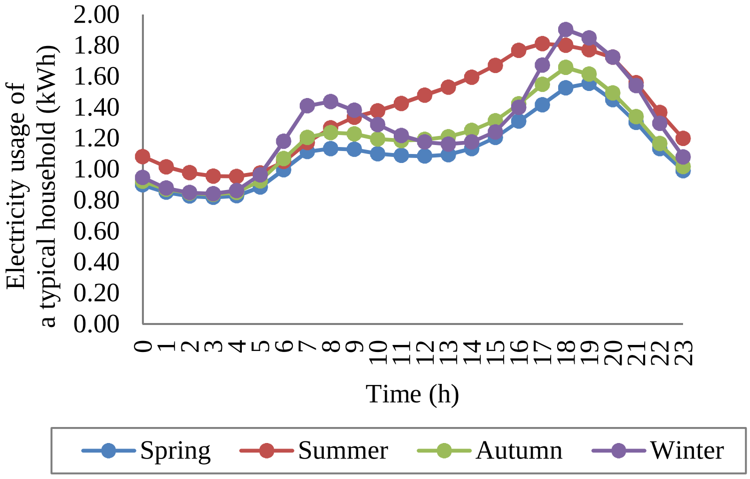

Fig. 3- The profile of the average hourly electricity usage of a typical household in the case-study area in each season

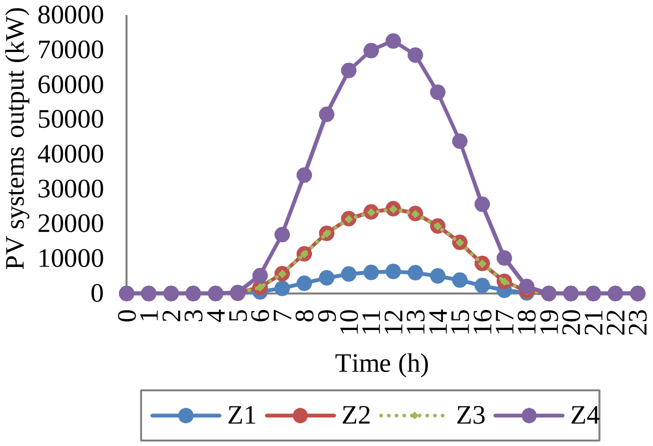

Fig. 4- Maximum PV systems output in each zone

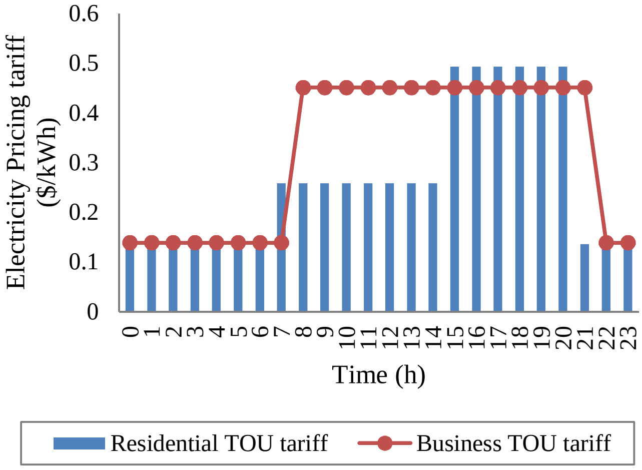

Fig. 5- Regulated TOU electricity tariffs for residential and business sectors implemented in the case-study

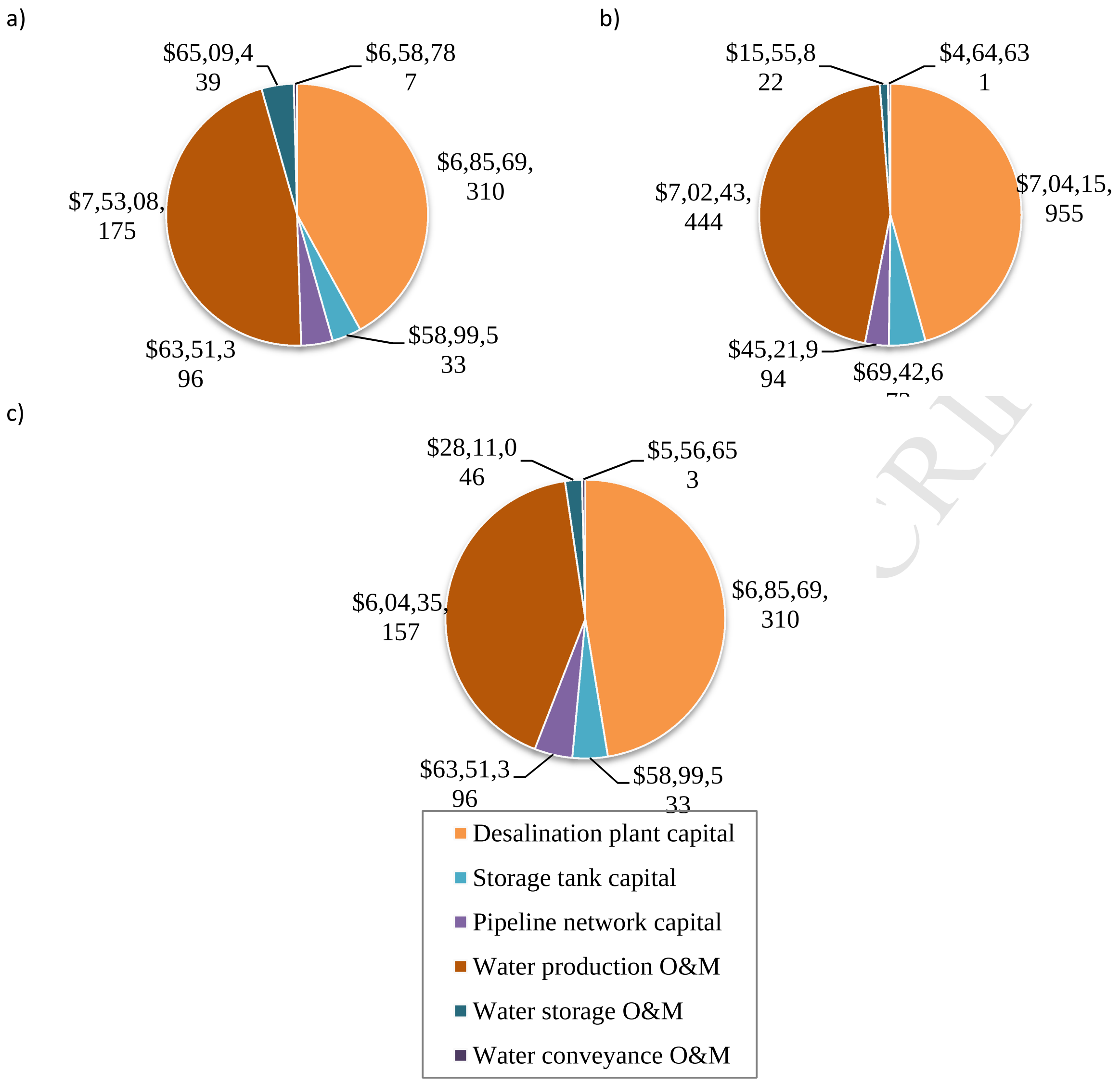

Fig. 6- Breakdown of the annualised total cost of the optimal desalination-based water supply system for three scenarios: a) *Fixed* b) *Semi-flexible* and c) *Flexible*

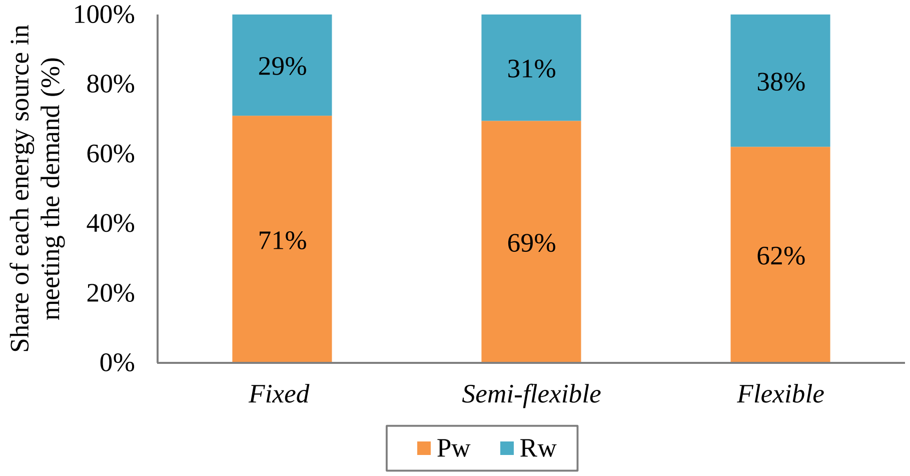

Fig. 7- Total share of surplus PV output (R^w) and grid electricity (P^w) in supplying water-related electricity demand

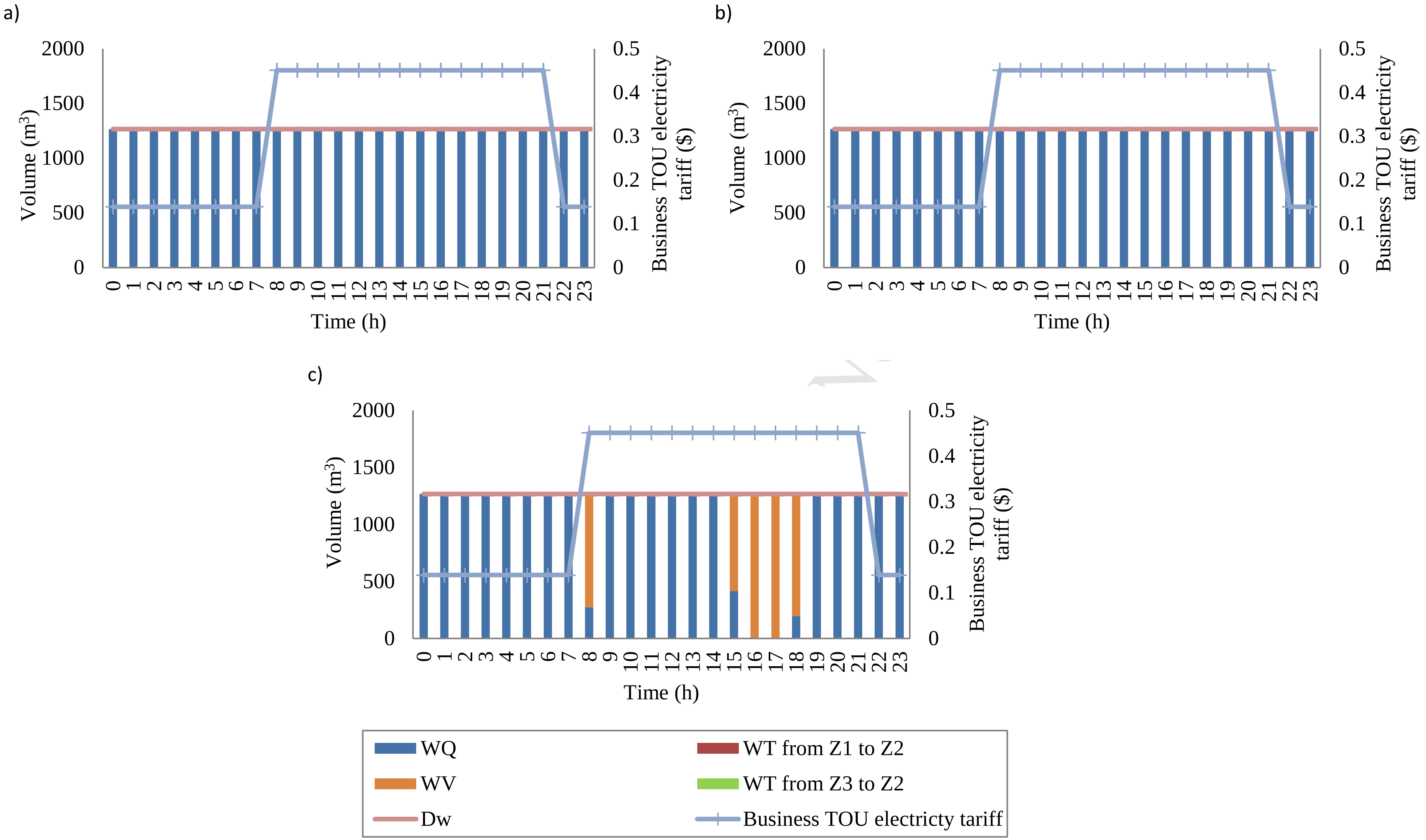

Fig. 8- Optimal water supply operation at the point of demand (D^w) in zone 2 during summer in three scenarios: a) *Fixed* b) *Semi-flexible* and c) *Flexible*, including water assigned directly from desalination plant (WQ), desalinated water transferred from other zones (WT) and desalinated water assigned from storage tank (WV)

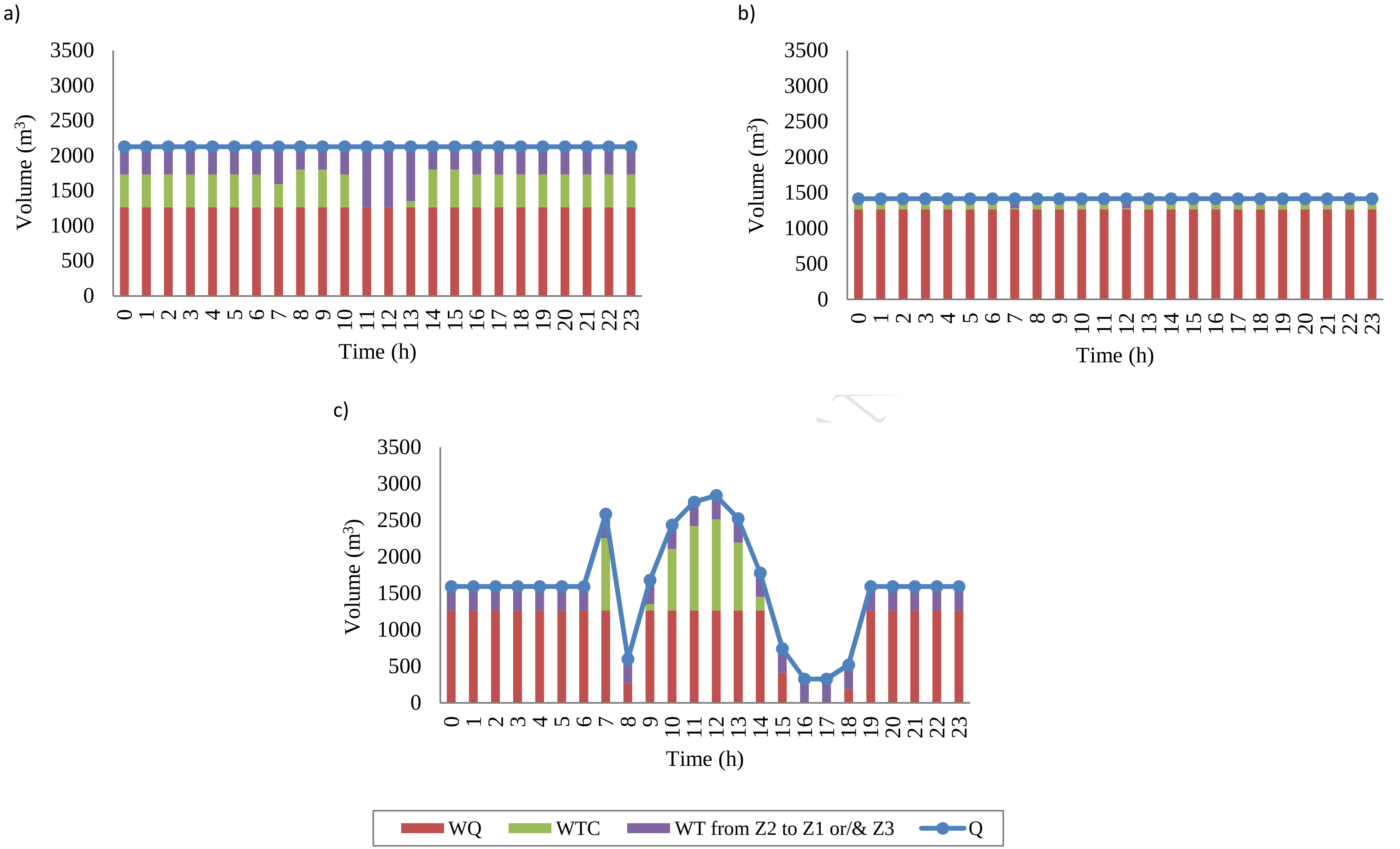

Fig. 9- Optimal water supply operation at the point of production in zone 2 during summer for three scenarios: a) *Fixed* b) *Semi-flexible* and c) *Flexible*, including water assigned directly from desalination plant (WQ), water pushed for storage from desalination plant (WTC), desalinated water transferred to other zones (WT) and desalinated water produced (Q)

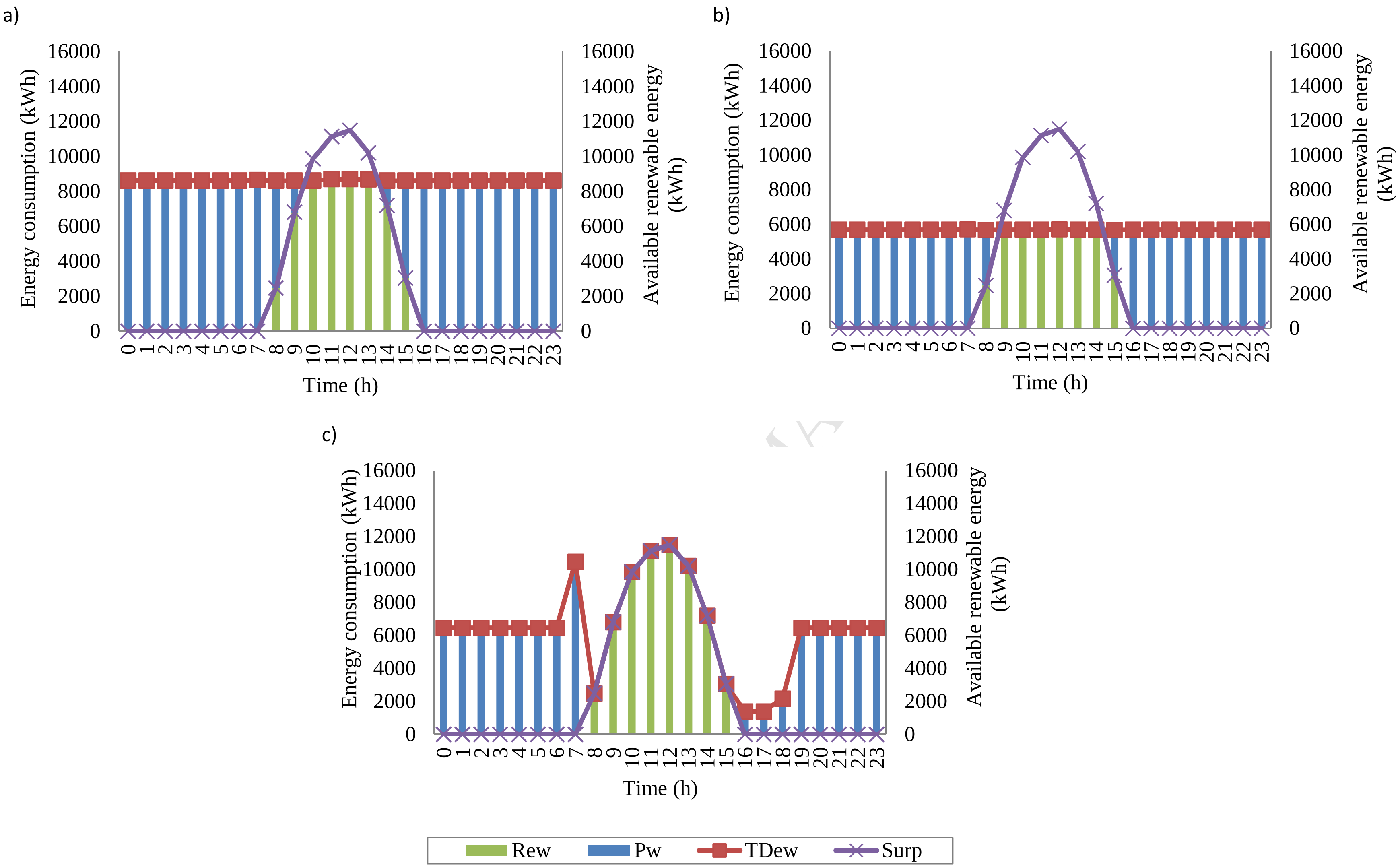

Fig. 10- Surplus PV output fed to the electrical grid (Surp) in zone 2 as well as optimal share of each energy source including surplus PV output (RE^w) and grid electricity (P^w) in meeting the total water-related energy demand (TD^{ew}) during summer for three scenarios: a) *Fixed* b) *Semi-flexible* and c) *Flexible*

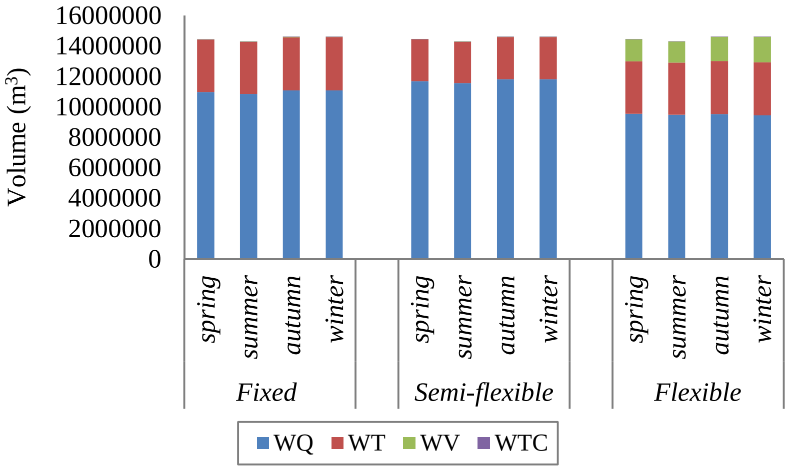

Fig. 11- The effect of seasonal changes on optimal operation of water supply system to meet the total water demand within case-study boundary during the one-year planning horizon

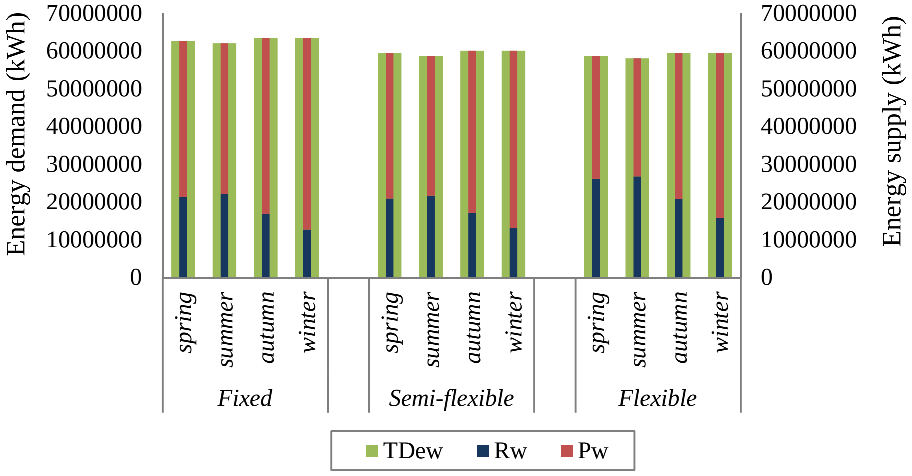

Fig. 12- The effect of seasonal changes on the share of energy sources to meet the total water-related energy demand within case-study boundary during the one-year planning horizon

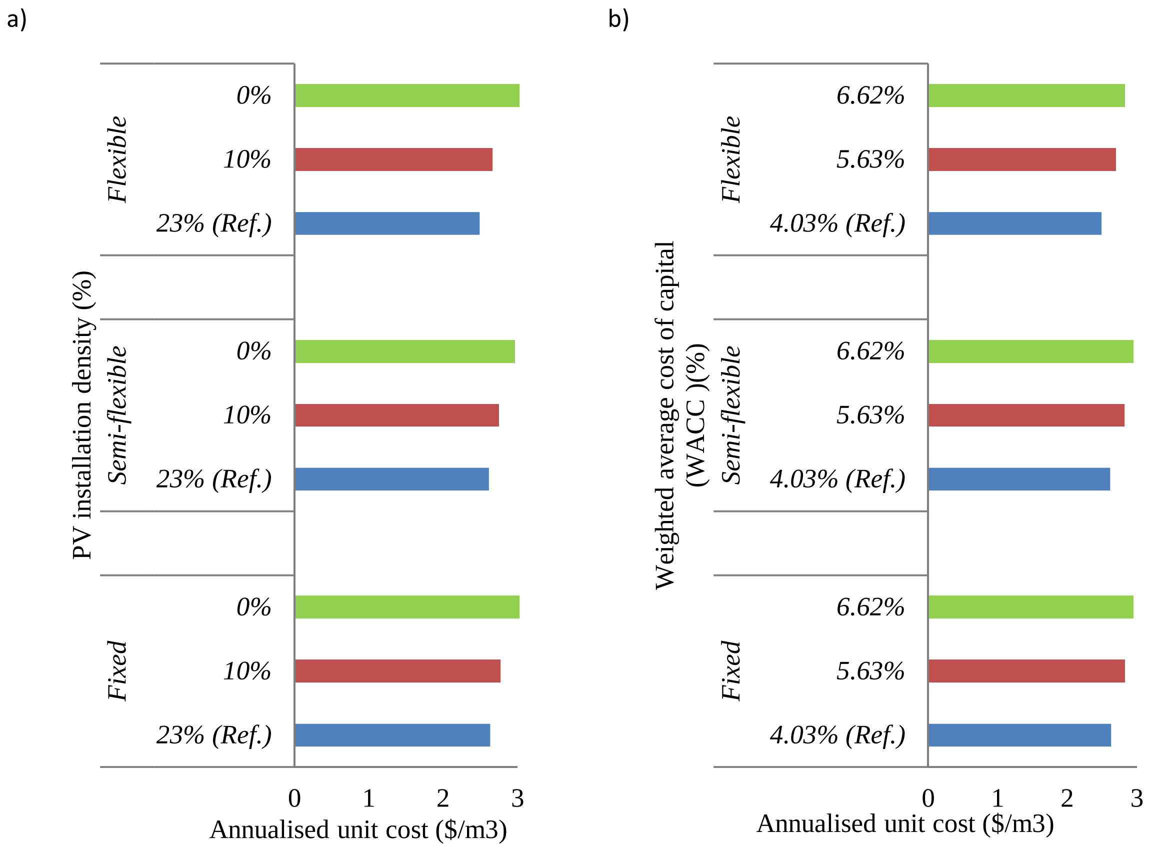

Fig. 13- Comparison of annualised unit cost of the optimal water supply system in *fixed*, *semi-flexible* and *flexible* scenarios: a) for three different PV installation densities and b) for three different financial rates

Figure No.	Sizing/preference for colour
Fig. 1- Depiction of proposed two-level optimisation model	2-column fitting image (page layout: landscape)/preference for colour: online only
Fig. 2- Zones boundaries, possible locations for potential desalination plants, storage tanks and connecting pipelines, as well as spatial distribution of average annual water demand	single column fitting image
Fig. 3- The profile of the average hourly electricity usage of a typical household in the case-study area in each season	1.5 column fitting image/ preference for colour: online only
Fig. 4- Maximum PV systems output in each zone	single column fitting image/ preference for colour: online only
Fig. 5- Regulated TOU electricity tariffs for residential and business sectors implemented in the case-study	single column fitting image/ preference for colour: online only
Fig. 6- Breakdown of the annualised total cost of the optimal desalination-based water supply system for three scenarios: a) *Fixed* b) *Semi-flexible* and c) *Flexible*	single column fitting image (each graph of a, b and c)/ preference for colour: online only
Fig. 7- Total share of surplus PV output (R^w) and grid electricity (P^w) in supplying water-related electricity demand	1.5 column fitting image/ preference for colour: online only
Fig. 8- Optimal water supply operation at the point of demand (D^w) in zone 2 during summer in three scenarios: a) *Fixed* b) *Semi-flexible* and c) *Flexible*, including water assigned directly from desalination plant (WQ), desalinated water transferred from other zones (WT) and desalinated water assigned from storage tank (WV)	1.5 column fitting image (each graph of a, b and c)/ preference for colour: online only
Fig. 9- Optimal water supply operation at the point of production in zone 2 during summer for three scenarios: a) *Fixed* b) *Semi-flexible* and c) *Flexible*, including water assigned directly from desalination plant (WQ), water pushed for storage from desalination plant (WTC), desalinated water transferred to other zones (WT) and desalinated water produced (Q)	1.5 column fitting image (each graph of a, b and c)/ preference for colour: online only
Fig. 10- Surplus PV output fed to the electrical grid (Surp) in zone 2 as well as optimal share of each energy source including surplus PV output (RE^w) and grid electricity (P^w) in meeting the total water-related energy demand (TD^{ew}) during summer for three scenarios: a) *Fixed* b) *Semi-flexible* and c) *Flexible*	1.5 column fitting image (each graph of a, b and c)/ preference for colour: online only
Fig. 11- The effect of seasonal changes on optimal operation of water supply system to meet the total water demand within case-study boundary during the one-year planning horizon	1.5 column fitting image/ preference for colour: online only
Fig. 12- The effect of seasonal changes on the share of energy sources to meet the total water-related energy demand within case-study boundary during the one-year planning horizon	1.5 column fitting image/ preference for colour: online only
Fig. 13- Comparison of annualised unit cost of the optimal water supply system in *fixed*, *semi-flexible* and *flexible* scenarios: a) for three different PV installation densities and b) for three different financial rates	single column fitting image (each graph of a and b)/ preference for colour: online only

Highlights

- Surplus output from grid-connected photovoltaics is applied for urban water supply
- A two-level optimisation model is used for investment and operational decisions
- The spatial aspect of the problem is taken into account
- Operational scenarios analysis is conducted for water and energy supply to Perth
- Sensitivity analysis is done towards photovoltaic installations and financial rates