Development of an Optimisation Framework for Integrated Planning of the Renewable Energy and Water Supply

by

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Declaration

I declare that this thesis is my own account of my research and contains as its main content work, which has not previously been submitted for a degree at any tertiary education institution.

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Abstract

Urbanisation, population growth, and economic development have turned cities into largest water resources consumers. The adverse effect of climate change adds even more pressure on the existing water resources and makes it inevitable to consider drought-proof technologies such as desalination to supply the increasing urban water demand. However, the energy intensity of these technologies questions the sustainability of their long-term application and highlights the necessity of considering renewable energy sources to meet their energy demand.

In land-restricted urban areas, electricity from residential rooftop grid-connected photovoltaics (PVs) is a promising clean energy source, which can contribute to the urban energy mix. Although, the intermittency of the surplus output from PV systems is a barrier for a higher potential capacity of their installation. This surplus energy is a result of the mismatch between energy generation and demand occurring during the day in the residential sector.

This study aims to address both issues of sustainable water supply and surplus PV output intermittency in the context of the integrated water and energy management. Different water supply system components are considered as deferrable loads exhausting surplus PV output at the time of its generation. Accordingly, the optimal decisions for a desalination-based water supply system driven by grid electricity and surplus PV output (hybrid energy sources) are achieved using mathematical optimisation modelling supported by three tools: geographical information system (GIS), system advisor model (SAM), and Excel.

The linear programming model is first developed for the optimal scheduling of the integrated system and then extended as a mixed integer linear programming (MILP) model to also include the optimal strategic decisions. The model considers temporal and spatial water and energy demands, supply systems configuration, resources capacities and associated costs as well as electricity pricing tariffs. It, then, gives the optimal solution such that it leads to the greatest compatibility of the water supply system operation with available renewable energy and the least system costs over the defined planning horizon. The model is tested for current and future water supply in an urban area located in the north-western corridor of Perth, Western Australia (WA). However, it can be applied to any urban area located in arid and semi-arid regions.

The initial results for optimal operation of the system showed that considering surplus PV output as a part of water-related energy mix leads to higher PV installation capacity and significant savings in operational and maintenance (O&M) costs. Compared to fixed (yearly basis) and semi-flexible (seasonal basis) operation of the water supply system, flexible (hourly basis) mode of operation resulted in the most compatibility with available surplus PV output; and therefore, a higher share of renewable energy in water-related energy mix. It also showed higher economic benefits over other operational scenarios in terms of the total system costs. In all cases, however, the availability of surplus PV output is a detrimental factor to the economic performance of the system.

The optimal long-term planning for the water supply system operated compatibly with available renewable energy resulted in a multistage construction and expansion of water supply components for sustainable demand supply. In addition, it was shown that decentralised water supply systems operated in flexible mode, leads to less discounted total cost of the system and higher level of potential PV uptake capacities, compared to centralised water supply systems operated in fixed mode; even though the surplus PV output is considered as a part of their energy mix. In this regard, the effect of the householders' free will for up taking PV systems and probable imposed O&M costs of the flexible mode of operation needs to be taken into account if the decentralised scenario is chosen to be implemented in practice.

It was also indicated that considering the effect of the indirect environmental impact of purchasing grid electricity for water supply affects the optimal results in terms of system components capacity as well as the timing of the construction and expansion of the water supply system. It also results in less indirect greenhouse gas emission and higher discounted total cost of the system over the planning horizon. In this respect, the generation source of purchased electricity plays a significant role.

Finally, the achieved insight into the different aspects of the desalination-based water supply system driven by hybrid energy sources led to the series of recommendations for future studies in the context of the integrated water and energy management.

A note on the thesis formatting

The thesis consists of 7 chapters presented as published or submitted research papers[1]. On the front page of each chapter, the information regarding the paper and authors contributions are provided. In separate sections, the additional texts clarify the connection between every two subsequent chapters. The formatted published papers are presented in Appendix 2.

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[1] The nomenclature is presented for each chapter individually. Also, the footnotes numbering is restarted for each Chapter.

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List of Publications

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Vakilifard N, A. Bahri P, Anda M, Ho G. An interactive planning model for sustainable urban water and energy supply. Appl Energy. 2019; 235:332-345.

Vakilifard N, A. Bahri P, Anda M, Ho G. The effect of indirect GHG emissions costs on the optimal water and energy supply systems. In: Computer aided process engineering. Elsevier; Forthcoming 2019.

Abbreviations

ACO	Ant Colony Optimisation
BaPSi	Battery-Photovoltaic-Simulation
BWRO	Brackish Water Reverse Osmosis
CCHP	Combined Cooling, Heat and Power
CRF	Capital Recovery Factor
DER-CAM	Distributed Energy Resources Customer Adoption Model
DP	Dynamic Programming
EEI	Energy Efficiency Indicator
EIO-LCA	Economic Input-Output Lifecycle Assessment
ERA	Economic Regulation Authority
FiT	Feed-in Tariffs
GA	Genetic Algorithm
GHEST	Genetic Heritage Evolution by Stochastic Transmission
GHG	Greenhouse Gas
GIS	Geographical Information System
GRG	Generalised Reduced Gradient
HDH	Humidification-Dehumidification
HRSG	Heat Recovery Steam Generator
INFINIT	Interdependent Network Flows with Induced Internal Transformation
LCA	Life Cycle Assessments
LGA	Local Government Area
LT-MED	Low Temperature Multi-Effect Distillation
LP	Linear Programming
MCA	Multi-Criteria Analysis
MCS	Monte Carlo Simulation
METVC	Multi-Effect Evaporation Thermal Vapour Compression
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Nonlinear Programming
MIP	Mixed Integer Programming
MSF	Multi-Stage Flash
MVC	Mechanical Vapor Compression

NLP	Nonlinear Programming
NPC	Net Present Cost
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
NSGA	Non-dominated Sorting Genetic Algorithm
O&M	Operational and Maintenance costs
PHS	Pumped Hydro Storage
PRO	Pressure Retarded Osmosis
PSO	Particle Swarm Optimisation
PV	Photovoltaic
RO	Reverse Osmosis
SA	Simulated Annealing
SAM	System Advisor Model
SEC	Specific Energy Consumption
SWRO	Seawater Reverse Osmosis
TOU	Time-of-Use
TS	Tabu Search
WACC	Weighted Average Cost of Capital
WSS	Water Supply System
WDS	Water Distribution System

General introduction

Population growth and economic development, more than ever, raise concerns over water supply for the future demand. Currently, two-thirds of the world's population lives in water stress areas where they experience at least one month of water scarcity throughout a year. The effect of water shortage is more pronounced in urban areas as it is projected that the world's population will increase from around one billion people to 8.6 billion in 2030, from which more than 10 million will be city inhabitants[1].

This situation along with drought and extreme rainfall variability under climate change is turning natural water resources into unreliable water supply options and calls for incorporating drought-proof alternatives, such as desalination, as part of the urban water supply system. The intensive energy consumption of these technologies, however, questions the sustainability of their long-term application and highlights the necessity of considering renewable energy sources to meet the associated energy demand. It also suggests that the issue of water supply can be fully addressed only in the context of integrated water and energy management, where the concept of the water and energy nexus[2] is applied to secure the efficient and sustainable use of resources.

In cities located in areas enjoying profuse solar irradiance, residential grid-connected rooftop photovoltaics (PVs) is a promising option to generate clean energy. However, the higher level of PV installation is generally limited to the hosting capacity of the existing electrical grid to deal with the intermittency of surplus PV output, daily fed into it. This surplus energy is generated due to the mismatch between the load and electricity supply in the residential sector. Considering water supply system components as deferrable loads to the electrical grid in order to create compatibility between the two, can be, therefore, a solution for both sustainable water and clean energy issues in the context of the integrated water and energy management.

In this regard, Al-Nory and El-Beltagy (2014), for the first time, presented the idea of considering desalination plants as a deferrable load and developed a model for the optimal operational scheduling of centralised desalination plants integrated with smart grid to combat the intermittency of grid-connected renewable energy source. However, reviewing the

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[1] Radcliffe JC. The water energy nexus in Australia – The outcome of two crises. Water-Energy Nexus. Forthcoming 2018.

[2] Water and energy nexus refers to the linkage between water and energy resources. Chapter 1 explains this concept in more detail.

existing optimisation studies, there is still a large knowledge gap when it comes to optimising different aspects of such integrated systems[3], especially optimising water and energy supply while taking into account their interaction simultaneously. Therefore, considering surplus PVs output as a part of the water-related energy mix, this study attempts to address the overarching research question of “how can an urban desalination-based water supply system and potential capacity of grid-connected PV uptake be optimised in an interactive way?”. This question, therefore, led to the aim of the research as to “develop an interactive optimisation model for short-term operational and strategic decisions of an urban desalination-based water supply system driven by grid electricity and surplus PV output” in order to investigate the economic and environmental impacts of such water supply system as well as its effect on potential PV uptake capacity in a long-term horizon.

1. Scope of the research

In this study, desalination-based water supply system was chosen to be integrated with hybrid energy sources (electrical grid and PV system) in order to meet urban water and energy demand in arid and semi-arid regions. Water supply system consisted of desalination plants, storage tanks and a pipeline network. Seawater reverse osmosis was selected as a desalination technology due to its capability in adjusting with intermittent renewable energy sources[4]. As for the energy system, the capacity of the existing resources including grid electricity and PV systems output were taken into account; the former was estimated based on the distribution substations capacities and the latter was determined according to the system size as well as economic, technical and subjectivity criteria. The spatial layout of both water and energy systems components as well as different time scales from hourly to seasonal and yearly was considered.

The costs analysis covered investment and operational and maintenance expenses for the water supplier as well as residential electricity costs.

Accordingly, the question of the research was addressed considering the boundary of the studied integrated system indicated in Fig. 1. Three tools of geographical information system, excel and system advisor model were deployed together with GAMS software in which the optimisation problem was mathematically coded and solved.

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[3] Chapter 1 presents a comprehensive literature review and summarises the existing knowledge gaps.

[4] For comprehensive review of renewable energy-driven desalination technologies, the reader is referred to: Ghaffour N, Bundschuh B, Mahmoudi H, Goosen MFA. Renewable energy-driven desalination technologies: A comprehensive review on challenges and potential applications of integrated systems. Desalin. 2015; 356: 94-114.

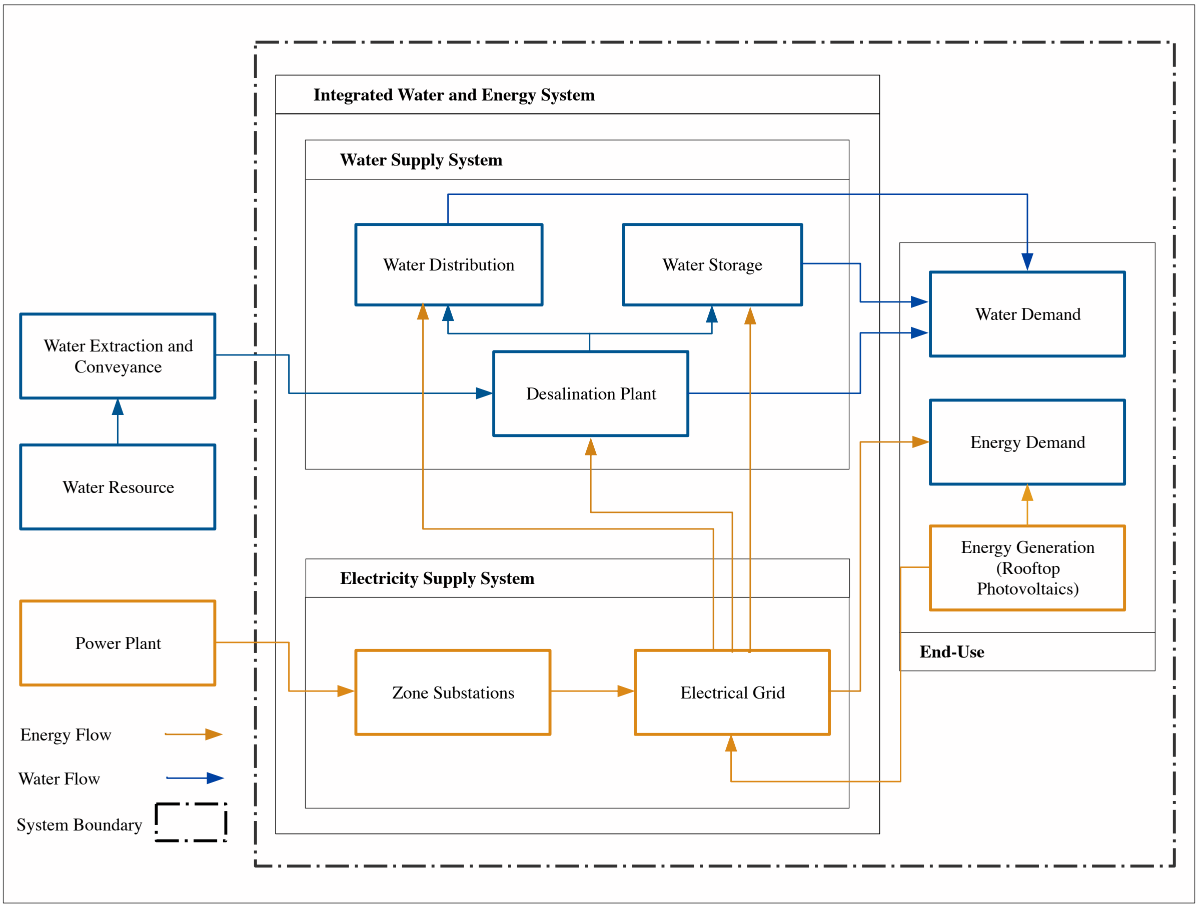

Fig. 1- Graphical overview of the integrated water and energy system boundary

2. Research objectives and thesis structure

The thesis was structured such that each chapter (as a paper) addresses individually a research objective derived from a subset of research questions consisting of a core question and several sub-questions. The research objectives and the core questions alongside a brief description of the rationale of how they were addressed within the thesis structure are presented below. The sub-questions are discussed in the associated chapters.

- Literature review and identify the existing knowledge gaps in optimisation studies in water supply side of the nexus (Chapter 1)

  In Chapter 1, the research objective is to determine the optimisation modelling techniques suitable to be used in water and energy nexus problems, the aspects which need to be considered in their modelling framework as well as the existing knowledge gaps. To address this research objective, a comprehensive literature review on the existing optimisation studies in water supply side of the water-energy nexus was conducted from three aspects of the system energy sources, centralised or decentralised approaches and system parameters uncertainties and the knowledge gaps were identified accordingly. The future direction of research was then described including the optimisation problem through which this study addresses the existing knowledge gaps. The publication below arises from the work in this chapter:

Vakilifard N., Anda M., A. Bahri P., Ho G. The role of water-energy nexus in optimising water supply systems- Review of techniques and approaches. Renew Sustain Energy Rev. 2018; 82: 1424-1432.

- Develop an optimisation model for the operation of an urban desalination-based water supply system driven by hybrid energy sources (Chapter 2)

  In Chapter 2 the research question is "if it is worthwhile (from economic and PV installation capacity points of view) to consider surplus PV output as a part of water-related energy mix." In this chapter, four data categories were defined capturing temporal-spatial aspects of the problem, water and energy supply systems specifications as well as associated costs. The data categories were then introduced to a mathematical optimisation model developed for operation of the system with this assumption that water production and storage can vary in different time blocks of the representative days. The question was then answered by comparing the results of the model, applied to an urban area located in the north-western corridor of Perth, Western Australia (WA), for two scenarios of the desalination-based water supply system driven by hybrid energy sources (grid electricity and surplus PV output) and when it is fuelled only by grid electricity (base scenario). The publication below is associated with the work in this chapter:

  Vakilifard N, A. Bahri P, Anda M, Ho G. Water security and clean energy, co-benefits of an integrated water and energy management. In: Computer aided process engineering. Elsevier; 2017. Vol. 40, p. 1363-1368.

- Investigate the effect of different operational approaches on both optimal investment and operation of the urban desalination-based water supply system driven by hybrid energy sources (Chapter 3)

  Considering the assumption made regarding the mode of system operation in Chapter 2, this question arises "whether operating the water supply system in flexible mode of operation improves its performance (i.e. economic aspects) compared to currently common modes of operation implemented in real-world cases." This question was answered in Chapter 3. Following a relevant literature review, in this chapter, the model as well as data categories were extended to capture both operational and investment decisions of the water supply system. The flexible operational scenario (for the same case-study) was compared with two other operational scenarios applied in practice and the results were discussed in details. The publication below arises from the work in this chapter:

Vakilifard N, A. Bahri P, Anda M, Ho G. A two-level decision making approach for optimal integrated urban water and energy management. Energy. 2018; 155:408-425.

- Develop an optimisation model for long-term planning of the urban desalination-based water supply system driven by hybrid energy sources incorporating short-term operational constraints (Chapter 4)

  Chapter 4 addresses the research question of "what is the optimal construction and expansion planning of water supply system driven by hybrid energy sources." To answer this question, the input data was expanded and the optimisation model was extended such that the selected operational scheduling constraints (Chapter 3) were integrated with yearly planning constraints considered in Chapter 4 to achieve optimal short-term operational and strategic decisions of such water supply system. The publication below is the outcome of the work in this chapter:

  Vakilifard N, A. Bahri P, Anda M, Ho G. Integrating real-time operational constraints in planning of water and energy supply. In: Computer aided process engineering. Elsevier; 2018. Vol. 43, p. 313-318.

- Develop an optimisation model to simultaneously address the evolution of potential PV uptake capacity as well as strategic and operational decisions of the urban desalination-based water supply system driven by hybrid energy sources (Chapter 5)

  The research question in this chapter is "whether the application of an interactive model for optimal water supply system driven by hybrid energy sources improves the economic performance of the system as well as potential PV uptake capacity in a long-term horizon." This question was addressed by developing an optimisation model (on the basis of the model developed in Chapter 4) which reaches the final optimal solution with a novel approach. The results of the model for the water supply system with the flexible operational scheduling (applied in Chapters 3 and 4), were then compared with two other scenarios including business as usual practices. The work in this chapter resulted in the publication below:

Vakilifard N, A. Bahri P, Anda M, Ho G. An interactive planning model for sustainable urban water and energy supply. Appl Energy. 2019; 235:332-345.

- Investigate the effect of indirect greenhouse gas (GHG) emissions associated with purchasing grid electricity for water supply on the optimal strategic and operational decisions of the urban desalination-based water supply system driven by hybrid energy sources over the long planning horizon (Chapter 6)

  Chapter 6 answers the research question of "how are the optimal water supply system and associated potential PV uptake capacity changed if the effect of indirect GHG emissions is considered as a part of the optimisation model." To address this research question, the objective function of the optimisation model developed in Chapter 5 is extended so as to include the indirect GHG emissions costs associated with purchasing grid electricity for water supply. The results were then compared with the selected scenario in Chapter 5 and discussed in details. The following is the publication derived from the work in Chapter 6.

  Vakilifard N, A. Bahri P, Anda M, Ho G. The effect of indirect GHG emissions costs on the optimal water and energy supply systems. In: Computer aided process engineering. Elsevier; Forthcoming 2019.

- Conclusions and recommendations for future research (Chapter 7)

  Chapter 7 presents a brief description of how the thesis chapters addressed the research objectives through summarising the work in each chapter and the main contributing outcomes. It also contains the overall conclusion obtained in each chapter. This chapter ends with a number of recommendations for future research.

Table 1 summarises different aspects of the proposed optimisation model developed at each stage. It is notable that the model statistics for various scenarios are described in the associated chapters.

Table 1- Summary of the main characteristics of the proposed optimisation model developed at each stage

Main decision variables	Optimisation technique	Objective function	Model constraints [a]		Time scales	Chapter
			Common	Specific/added		
Optimal operational decisions	Two- level linear optimisation programming	• Residential energy cost • Water supply system operational cost	• Residential energy balance • Renewable energy source constraints • Water-related energy balance • Energy resources constraints • Water balance • Water distribution and storage constraints • Water production constraints		Four daily time blocks, two seasons	2
Optimal operational and investment decisions	Two-level mixed integer linear programming	• Total residential energy cost • Annualised total cost of water supply system		• Water supply system components capacities	Hourly, four seasons	3
Optimal short-term operational and long-term construction and expansion planning decisions	Two-level mixed integer linear programming	• Discounted residential electricity cost • Discounted total cost of water supply system		• Water supply system components capacities • Unused renewable energy constraint	Hourly, two seasons, twenty years	4
Interactive operational and planning model for water and energy supply	Two-level mixed integer linear programming	• Discounted total residential benefit of installing PV systems • Discounted total cost of water supply system		• Maximum potential PV output • Surplus PV output • Water supply system components capacities	Hourly, two seasons, fifteen years	5

[a] The formulation of the equations and the model input are slightly different in each chapter depending on the characteristics of the stated problem. This is especially the case in Chapter 5 in which the interactive model is developed and other inputs such as subjectivity index is also considered.

This thesis presents an optimisation modelling framework to address the issue of water and energy supply in urban areas located in arid and semi-arid regions and uses the case-study of Perth (WA) to show the capabilities of the model. The mathematical model developed in this study helps to explore the effects of including surplus PVs output in water-related energy mix on the optimal urban desalination-based water supply system. It also leads to better understanding of the impact of considering water supply system components as deferrable loads to the existing electrical grid, on the evolution of potential PV uptake capacity. This model, therefore, sheds light on the interaction of water and energy resources in urban areas and assists in making better informed short and long-term decisions in both water and energy sectors.

Foreword to Chapter 1

As mentioned previously (General introduction), the necessity of employing drought-proof but energy intensive water supply options makes it inevitable to address the issue of sustainable urban water supply through understanding of the nature of water and energy nexus.

Water and energy nexus refers to the linkage between water and energy resources and can be defined as a system-of-systems consisting of two groups of water and energy infrastructures in which the full value chain of energy in the former and the full value chain of water in the latter are described[1]. A better understanding of the water and energy nexus can be achieved through developing modelling frameworks that could allow the assessment of the implications of different water and energy scenarios. In water supply side of the nexus, this is mainly associated with design, operation, and planning of the water supply system driven by different energy sources. It also includes the modelling frameworks addressing various aspects of the cogeneration systems where the requirements of both water and energy supplies are simultaneously taken into account. In this regard, the optimisation modelling is a strong tool can be applied to solve such problems concisely, quantitative analysis of the solutions and yield the best result that leads to making the most efficient use out of available resources.

Accordingly, Chapter 1 presents a comprehensive literature review on the optimisation studies in water supply side of the nexus. It highlights the existing knowledge gaps in the field and introduces an optimisation problem through which they can be potentially addressed.

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[1] Santhosh A, Farid AM, Youcef-Toumi K. Real-time economic dispatch for the supply side of the energy-water nexus. Appl Energy. 2014;122:42-52.

Chapter 1- The role of water-energy nexus in optimising water supply systems- Review of techniques and approaches

This chapter has been published in the journal of Renewable and Sustainable Energy Reviews as a literature review paper.

Reference

Vakilifard N., Anda M., A. Bahri P., Ho G. The role of water-energy nexus in optimising water supply systems- Review of techniques and approaches. Renew Sustain Energy Rev. 2018; 82: 1424-1432.

The formatted published paper is presented in Appendix 2, Section A2.1.

Authors contribution

Contributor	**Statement of contribution**	**Signature**
Negar Vakilifard*	All the literature review, design of the study, writing the manuscript and revising it based on the received feedbacks	
Parisa A. Bahri	Proposing the project concept, critical review of the paper, giving feedback on the draft and principal supervisor of the project	
Martin Anda	Proposing the project concept, peer review of the paper and co-supervisor of the project	
Goen Ho	Proposing the project concept, peer review of the paper and co-supervisor of the project	

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Abstract

Considering water-energy nexus in optimising water supply systems not only ensures the sustainability of the water supply for increasing water demand but also diminishes water-related energy and environmental concerns. This paper presents a review highlighting knowledge gaps in optimisation models related to the water-energy nexus in water supply systems or “water supply side of the nexus”. Studies reported in the literature are categorised and systematically analysed in terms of different energy sources, centralised/ decentralised approaches and system parameters uncertainties. Several major gaps are identified. These include the lack of optimisation models capturing spatial aspects as well as environmental impacts of the nexus problems. The shortage of models considering uncertainties associated with water demand and renewable energy supply is another knowledge gap in this area. However, the main gap is the absence of models for optimising long-term planning of water supply system considering renewable energy within an urban context. Accordingly, based on this review, we have suggested pointers for future studies in the water supply side of the nexus.

Keywords: Water-energy nexus, Water supply system, Renewable energy source, Hybrid energy source, Optimization

1. Introduction

Considering water-energy nexus in planning, design and operation of a water supply system not only ensures the sustainability of the system but also conserves energy and minimises related greenhouse gas (GHG) emissions. Currently, the water industry is responsible for 2-3% of the global energy consumption [1]. In some developed countries such as the U.K., the contribution of the water supply system to nation's electricity consumption is around 3%, accounting for about 1% of all GHG emission per annum [2, 3]. In the U.S., on the other hand, the water supply system constitutes 13% of total energy usage and 5% of all national GHG emissions annually [4].

Although compared to other sectors, the contribution of the water industry to energy consumption and related GHG emissions is relatively low; it is increasing and ignoring it can escalate energy usage and accelerate climate change which consequently affects the sustainability of available water resources. In addition, by 2050, the world's population will be around 9.7 billion people and more than 25% will live in regions exposed to extreme water shortages [5, 6]. Therefore, it is foreseeable that deployment of energy intensive drought-proof technologies such as desalination in water supply systems will become inevitable leading to higher water-related energy intensity and environmental impacts in the future [7].

The significant role of quantitative analysis to understand the water-energy nexus in water supply systems and to reveal short and long-term implications of investment decisions and conservation policies in both sectors has been generally accepted. Nair et al. [7] reviewed the interactions of water-energy-GHG in urban water supply systems focusing on applied environmental impact assessment tools and energy intensity analysis. Kenway et al. [8] systematically analysed studies mainly regarding energy intensity in water resource management and life cycle assessments (LCA) and categorised them based on the research objectives, dimensions and study scales. In another review paper, Gude [9] provided a detailed view of the energy footprint in water supply infrastructures and wastewater facilities. However, to the best of our knowledge, none of the previous reviews looked into optimisation modelling of water supply systems in the context of water-energy nexus taking into account the types of the energy sources, centralised/decentralised system approaches and system parameters uncertainty.

This paper presents a comprehensive review of the optimisation models on the water-energy nexus in water supply systems or "water supply side of the nexus". The review includes those models which consider the energy aspect of different components of water supply systems, located in various points of the supply chain from a source to an end-use, to meet water demand for diverse purposes. We look into the existing optimisation techniques and approaches applied to planning, design and operation problems of the water supply side of the nexus from three aspects of (1) energy sources and system configuration, (2) centralised/decentralised system approaches and (3) system parameters uncertainty. The objective is to identify the gaps in the state of knowledge of this field and accordingly, to shed light on primary future directions of research in this area.

The remainder of the paper is as follows: Section 2 briefly surveys the existing optimisation techniques in water and energy systems and highlights potential techniques that can be applied to the problems on the water supply side of the nexus. Section 3 provides a narrative review of the application of these optimisation techniques in this side of the nexus. Section 4 and 5 indicate how the concepts of centralised/decentralised systems and uncertainty have been addressed in the existing optimisation models, respectively. Section 6 suggests directions for future studies and lastly, the conclusion is presented in Section 7.

2. Optimisation techniques applied to water and energy systems- a brief overview

Optimisation is one of the decision supporting tools applied to find the best feasible solution of the problem of interest [10]. Generally, in optimisation techniques, the objective function is minimised or maximised through values of the variables subjected to the constraints [11].

Detailed reviews of the optimisation techniques applied to water and energy problems are available for each sector. In [12-14], the authors gave a typology of the optimisation models used in energy systems. Specifically, the optimisation methods of renewable and sustainable energy supply problems were reviewed [15, 16]. In the water sector, on the other hand, some authors presented a review of applied optimisation techniques in urban water supply and water resource management [17-19].

In the context of the water-energy nexus, the optimisation techniques applied in each of these sectors separately can be potentially considered for nexus problems. However, the formulation of the optimisation problems depends on the characteristics of the system, the objective function and the environment of the operation.

The optimisation techniques applied to the systems in the water supply side of the nexus can be categorised broadly into mathematical and heuristic techniques.

- Mathematical techniques express the optimisation problems as a mathematical formula and in most cases guarantee to reach an optimal solution. The common mathematical optimisation techniques consist of linear programming (LP), mixed integer linear programming (MILP), nonlinear programming (NLP), mixed integer nonlinear programming (MINLP) and dynamic programming (DP) [18].

- Heuristic techniques are searching techniques which do not necessarily find an exact optimum solution or even determine how close it is to the optimum answer; however, they can solve highly complicated problems in a reasonable computation time and still find acceptable solutions [20]. The main heuristic techniques include simulated annealing (SA), tabu search (TS), particle swarm optimisation (PSO) and genetic algorithm (GA) [18].

These techniques are applied either individually, in combination with each other or in integration with simulation techniques/tools. In this paper, two optimisation techniques of the latter are referred to as hybrid techniques.

3. Optimisation techniques and approaches applied to the water supply side of the nexus

Optimal design, control and planning of water supply systems considering the water-energy nexus, not only conserves the existing resources but also prevents unnecessary investment, operational and management costs. Hence, optimisation problems in the water supply side of the nexus have received much attention; however, there are still major gaps in this field.

Based on the reviewed papers, it is evident that optimisation problems in this side of the nexus have been mainly investigated from either water or energy perspectives and there are very few studies which have simultaneously optimised the system for both aspects [21-23]. This is consistent with the conclusion drawn by Kenway et al. [8] through the review of city-scale water-energy nexus studies. They pointed out there is a lack of studies in water sector considering the interaction of the water and energy simultaneously.

On the other hand, the optimisation models explicitly considering the energy factor in water supply systems, have mostly addressed design or operation aspects, and there is a gap of knowledge regarding the long-term planning of these systems. This also involves the absence of studies capturing the spatial aspect of the nexus problem where optimisation can be applied to improve spatial coherence of land-use functions resulting in cost and energy saving. In addition, from the problem formulation point of view, these studies have considered the overall cost, energy consumption of water system or supplier’s revenue as the objective functions. Despite the importance of environmental aspects, they have been less taken into account in the optimisation structure and have been mainly addressed using LCA tools [7]. The optimisation models of the water supply side of the nexus are discussed in detail in the following sections and are summarised in Table 1.

Table 1- Summary of the optimisation models used in the water supply side of the nexus

Type of energy source	**Optimisation technique**	**Objective function**	**Model constraints** [b]			**Description of the system modelled**	**Ref.**
			Water perspective	Energy perspective	Others		
Fossil fuels	• Mathematical • Heuristic • Hybrid	• energy cost • energy consumption • total cost/revenue of the co-generation plant[a] • Environmental impact	• Mass balance • Water resource balance • Water storage tank constraints • Pipeline network constraints • Water production unit [c] constraints • Irrigation constraint • Ramping constraint • Economic constraint	• Energy balance • Pump energy consumption •Water production unit energy consumption • Conventional generation unit constraints • Distribution network constraints • Ramping constraint • Economic constraint	• Environmental impact constraints	• Water distribution system • Desalination supply system • Water and energy co-generation plant	[21-42]
Renewable energy	• Mathematical • Heuristic • Hybrid	• Total cost of the plant • Energy cost • Energy consumption • Energy production • Deficiency of power supply	• Mass balance • Water resource balance • Water storage tank constraints • Water production unit constraints • Economic constraint	• Energy balance • Renewable energy units constraints • Battery storage system constraints • Fuel constraint • Economic constraint	• Environmental impact constraint • Crop water demand constraint	• Off-grid desalination plant • Off-grid water pumping system	[43-52]

Table 1- (cont'd)

Type of energy source	**Optimisation technique**	**Objective function**	**Model constraints** [b]			**Description of the system modelled**	**Ref.**
			Water perspective	Energy perspective	Others		
Hybrid energy	• Mathematical • Heuristic • Hybrid	• Energy consumption • Total cost of the plant • Energy cost • Environmental impact • total annual profit of the plant	• Mass balance • Water storage tank constraints • Pumped water flow rate constraint • Water production unit constraints Economic constraint	• Energy balance • Renewable energy units constraints • Battery storage system constraints • Availability of renewable energy sources • Conventional generation unit constraints • Grid stabilisation constraint • Demand side management constraint • Economic constraint	• Environmental impact constraint	• Off-grid or grid connected desalination plant • Off-grid Water pumping system	[53-69]

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[a] Examples of water and energy co-generation plants are hydroelectric and thermal desalination plants

[b] Depends on the characteristics of the system, different combinations of the mentioned constraints have been applied in optimisation models in this side of the nexus

[c] Water production unit refers to either one or several component(s) of a desalination plant

3.1. Water supply systems driven by fossil fuel energy sources

Generally, in optimisation models of water supply systems powered by fossil fuels, energy considerations are implicitly expressed as part of the operational cost or as a constraint for energy saving and/or alleviation of the system GHG emissions [70-74]. However, it has been addressed as a fundamental factor in the optimisation of the water supply utilities which consume a high amount of energy.

It is commonly accepted that water distribution system (WDS) pumps are the high energy-intensive components of water supply systems [75]. In fact, 70 to 80 percent of the energy consumed in a surface water-based supply system is dedicated to pumping for distribution of the treated water [76]. On the other hand, the application of an advanced technology, such as desalination, increases the energy demand of the water supply system. According to Pacific Institute report, compared to other options of water supply such as importing water and recycled or brackish water treatment, seawater desalination requires considerably more energy, tantamount to 3.2-4.8 kWh/m^3 [77]. This has led to a growing interest in optimisation of the WDS operation and design of the desalination units in comparison with other components of the water supply system operating with fossil fuel energy sources.

From the operation point of view, Zheng and Huang [24] determined an optimum scheduling of water pumps using an improved DP algorithm. The model minimised the energy cost of the system operation considering the time-of-use (TOU) electricity pricing structure to meet water demand of a village in China. Giacomello et al. [25] employed a hybrid optimisation technique including LP and a greedy algorithm to obtain a near optimal real-life pump scheduling of a pumping system in a WDS. Both energy consumption and penalty factor were considered as the objective functions. In [26], the authors optimally scheduled the operation of a pumping system in a near real-time to minimise energy cost. Considering water demand at each time period as a stochastic process, they used parallel programming technique to solve the stochastic mixed integer programming (MIP) problem. The model was applied to drinking water supply in Granada, Spain. Similarly, López-Ibáñez et al. [27] determined an optimal pump scheduling by minimising the energy cost using a stochastic meta-heuristic algorithm, ant colony optimisation (ACO). They applied the model for Richmond WDS and compared the results with those obtained using conventional and hybrid GAs.

Cherchi et al. [28] considered two optimisation scenarios for energy cost and consumption of a drinking WDS in California. The system was composed of two water utilities, including several pumps and tanks. Using the combination of LP, NLP and advanced heuristic techniques, the optimum operational scheduling of the pumps was determined for each scenario. In the cost optimisation scenario, TOU electricity pricing structure and in the energy optimisation scenario, the GHG emission effects were taken into account. Stokes et al. [29] addressed both energy cost and GHG emissions of a WDS pumping operation using non-dominated sorting GA technique. In another study, Bene et al. [30] developed an optimisation model for a short-term pump scheduling employing neural search technique with GAs by minimising total energy cost. They compared their model with the optimal solution achieved by using conventional GA approach for a hypothetical WDS to present the abilities of their approach.

At the point of end use, Wanjiru and Xia [31] addressed the optimum operation of a rooftop rain water reservoir. They proposed a MINLP model to optimally schedule the irrigation of urban household gardens, considering a rooftop reservoir for harvesting rainwater and TOU electricity tariffs. The potable utility water was considered as a backup in case, the level of stored water decreased as a result of irrigation. The model optimised the use of the potable water as well as energy required for water pump through minimising the cost.

The optimal operation of desalination plants powered by fossil fuel sources has been addressed recently. For instance, Jiang et al. [32] developed an optimisation model to dynamically operate a large-scale desalination system plant consisting of multiple seawater reverse osmosis (SWRO) desalination plants and storage tanks. The NLP problem was solved to minimise the energy cost and it was applied to two hypothetical cases. Alternatively, more focus has been on the optimisation of water and energy co-generation plant. These systems are multi-utility plants in which different water and energy production components are integrated to supply both water and energy demands. Due to the higher efficiency and reliability of the supply and distribution networks, these systems are becoming attractive options [33].

El-Nashar and Khan [34] developed a MILP model to allocate the load to various generation units in a co-generation system to meet water and energy demands. Under static condition, it was assumed that the fluctuations of electrical load are very slow and the production of water in multi-stage flash (MSF) distillers is constant. The model minimised the fuel energy consumption of the co-generation complex using a bottom-up approach. In [21, 35], the authors presented a NLP model to address the optimal operation of a system consisting of multiple individual and co-generation water and power plants and their networks to meet water and power demand. The general optimisation formulation provided required flexibility to the model so that different technologies for each of the three types of plants could be considered. The model determined an optimum scheduling for water and energy production in each plant through minimising the cost of the total system. In [22] the same authors extended the model to address the real-time optimal flows in power and water networks considering extra constraints regarding safety requirements and water and power loss in the network lines. The effect of ramping power generation and electrical and water storage on the production level and operational costs was the focus of their latest study [23].

From the design aspect, Arai et al. [36] presented and compared two LP and MILP optimisation models to determine the route and the water flow rate in a WDS to satisfy water demand while minimising the energy usage. Bolognesi et al. [37] simulated and optimised a WDS using the integration of an optimisation tool, EPLANT model, and population-based genetic heritage evolution by stochastic transmission (GHEST) algorithm. Based on the proposed energy efficiency indicator (EEI) defined in terms of the “unavoidable minimum energy” of WDS, optimum pipe diameter was determined. In [38], authors developed a multi-objective two-stage stochastic integer optimisation model to cost-effectively design a reclaimed WDS. Considering construction and energy costs, the model determined the optimal pipe and pump sizes. Herstein et al. [39] optimised the design of a WDS using a multi-objective non-dominated sorting GA (NSGA-II). The model minimised capital costs, annual pumping energy use and environmental impact considering an economic input-output lifecycle assessment (EIO-LCA). The model was evaluated for the Anytown network.

The optimal design of water and energy co-generation plants has also been the focus of several studies. Shakib et al. [40] developed an optimisation model to design a water and energy co-generation plant consisting of a gas turbine, a heat recovery steam generator (HRSG) and a multi-effect evaporation thermal vapour compression desalination (METVC) plant. They used a GA to solve a thermodynamic-based multi-objective problem. The model maximised total exergetic efficiency (for both water and energy) while minimising total production cost. In another study, Rubio et al. [33], applied a MINLP to optimally determine the best configuration of a polygeneration system supplying water and energy demand in a hotel located on the Spanish Mediterranean coast. The system was the integration of a combined cooling, heat and power unit (CCHP) fed mainly by natural gas with reverse osmosis (RO) or low temperature multi-effect distillation (LT-MED) unit. The model maximised the net present value (NPV) considering the effects of the hotel location, type of the desalination plant, the operation mode, and the legal framework.

At the utility scale, such as desalination, the optimisation of the operation has been conducted to mitigate associated energy usage. For instance, Yechiel and Shevah [41] optimised the operation of a large SWRO desalination plant using LP model. The model minimised the energy cost of the plant considering time and peak load demand (time load tariff). The model was applied to Palmachim desalination plant in Tel-Aviv, Israel. Li [42] developed a constrained NLP model for the operation of a brackish water reverse osmosis (BWRO) to reduce its specific energy consumption (SEC).

3.2. Water supply systems driven by renewable energy sources

There is an evolving paradigm shift from the application of fossil fuel to renewable energy sources for the operation of water supply systems. In the literature, the most common configuration is the integration of an individual water supply component with one or several renewable energy systems equipped with storage systems, operated as a stand-alone or off-grid system. Since water scarcity is more likely to occur in the regions with abundant solar energy [78], the main focus has been on the optimal design and control of the integrated desalination plants and solar energy. In these system configurations, solar energy has met water-related energy demand either only or in combination with other sustainable energy sources. Most of the studies on this subject have targeted the detailed technological or operational aspects of such water supply system using either simulation tools/techniques [79-82] or their integration with experimental data [83-85]; others utilised the optimisation techniques.

Kyriakarakos et al. [43] combined parameters of TRNSYS simulation software with PSO to optimally design a renewable energy-based polygeneration system. The system consisted of photovoltaics (PVs), a wind turbine, a battery bank, a fuel cell, an electrolyser, a metal hydride tank and a RO desalination unit. The model was developed to meet electricity, transport fuel (hydrogen) and water needs while minimising the total cost of the system as well as penalty costs associated with battery, hydrogen and water. The model applied to a small island in the Aegean Sea. Similarly, Clarke et al. [44] compared PSO method and HOMER software to optimally size an integration of RO, hydrogen and solar energy sub-systems equipped with battery storage system. Using experimental and simulation data, a multi-objective problem was solved to minimise net present cost (NPC) and life-timeCO_2 emissions while meeting water and energy demands.

In [45, 46], authors employed GA techniques to determine the cost-effective configuration and size of a RO desalination process coupled with renewable energy sources and battery storage system to meet water demand. Similarly, in [47, 48], authors developed an optimisation model based on the GA technique to find the best configuration of a system consisting of PV panels, wind turbines, batteries and a RO plant, among different commercially available system devices. The model minimised the total cost of the water production for the life cycle of the plant. It was applied to a small community in South Tunisia. El-Morsi et al. [49] also applied the GA technique to optimally design a solar-powered humidification-dehumidification (HDH) desalination system such that the cost per m^3 of the fresh water is minimised. They assumed that if desired temperature couldn't be provided even by hot storage buffer due to the absence of solar energy supply, the desalination system would shut down and once again operate at its full capacity when the required temperature was met. In [78, 86], the authors briefly reviewed the optimisation techniques used in integrated solar-driven and wind-driven desalination units, respectively.

Stand-alone water pumping systems powered by wind or solar energy is another example of applying renewable energy sources in water supply systems. These systems are typically designed to supply water for domestic and irrigation purposes. However, of different systems of renewable energies, most of the optimisation models have been developed to dimension PV panels to power water pumping systems. One reason is owing to the high investment cost of these systems which makes it necessary to be accurately designed [87].

Glasnovic and Margeta [50, 51] adopted a hybrid optimisation model to optimally size a PV irrigation water pumping system without storage system such that the compatibility of the demand and availability of electric power was met. The integration of DP technique and simulation was employed to minimise the maximum nominal electric power of PV generator considering local climate, boreholes, soil, crops and method of irrigation. The model was tested for Osijek and Split, located in Croatia. Olcan [52] presented a techno-economic optimisation model for a stand-alone PV water pumping system for irrigation purposes in remote areas. The system equipped with water storage tank instead of battery storage system to deal with the renewable energy intermittency. Both cost and reliability aspects of the system have been addressed using a multi-objective optimisation technique. The model minimised both life cycle costs as well as the possibility of power supply deficiency to optimally determine the capacity of the system. The model was applied to a citrus trees yard in Antalya, Turkey. Lately, Gopal et al. [87] explained different renewable energy systems coupled with water pumping systems and briefly reviewed some of the existing optimisation models used for designing solar PV water pumping systems.

3.3. Water supply systems driven by hybrid energy sources

The application of hybrid energy sources for water supply system is becoming a promising research area. This is not only due to concerns over the unsustainability of fossil fuel energy sources and GHG emissions, but also because of the reliability delivered by hybrid energy sources to integrated energy and water supply systems. Generally, hybrid energy systems consist of both fossil fuel and renewable -based energy systems with storage facilities, operated in either grid-connected or off-grid modes.

The operational aspect of water supply systems powered by hybrid energy sources have received much attention and mostly addressed from energy point of view. Zejli et al. [53] optimally scheduled the flows of the energy from renewable sources (solar and wind) storage system and electrical network to use for a mechanical vapor compression (MVC) plant. A quadratic NLP model minimised the energy supplied from electrical network and simultaneously maximised the water production to meet freshwater demand. Palma-Behnke et al. [54] presented a MIP model for energy management of a smart microgrid composed of PV panels, a wind turbine, a diesel generator, a battery bank and a simple water supply system. The model optimised the operational schedule of the different energy sources as well as the water pump to meet electricity and water demands. It also minimised the use of diesel generator and operational costs of the microgrid.

In [55-57], the authors applied the PSO method to cost-effectively design and schedule an off-grid hybrid energy and water supply system equipped with different storage options including a pack of batteries, a water reservoir and a hot thermal storage. In another study, Vieira and Ramos [58] addressed the optimal performance of a pump station in a water supply system and the economic benefit of using wind energy for the water pumping. A LP model optimally scheduled the pump operation to meet water demand with minimum energy cost. In [59, 60], the authors established a management model for the integration of wind power, smart grid and water supply considering water storage instead of energy storage. A LP model was developed to optimally schedule the production and storage of the desalinated water from RO, MSF and multi effect distillation-vapor compression (MED-VC) plants such that the operational and management costs of the water production and storage as well as power plant electricity generation are minimised. Similarly, Perković et al. [61] formulated a LP problem using a high-level interpreted language, GNU Octave, to minimise energy cost for operation of a RO plant and a hybrid energy system consisting of renewable energy sources (solar and wind), a conventional power plant and a pumped brine storage as energy storage.

On the other hand, in [62, 63], the authors addressed the design aspect of the integrated system. They applied a techno-based algorithm and an iterative optimisation technique to achieve the cost-effective size of a storage-equipped hybrid energy system integrated with a RO unit. Salcedo et al. [64] presented a mathematical model for the optimal configuration and operation of a RO plant coupled with a solar Rankine cycle unit applying a gas fired heater as a backup system to overcome the intermittent nature of the renewable energy. The MINLP model minimised total cost of the system as well as related environmental impacts defined by LCA principles. In the next study, the same authors applied dimensionality reduction technique in multi-objective optimisation model for identification of the environmental impacts based on the impact assessment method, Eco-indicator 99. The model consisted of 12 objective functions including unitary production cost as well as 11 environmental indicators representative of the ecosystem quality, human health and resource damage categories [65]. Similarly, Rubio-Maya et al. [66] applied a MINLP model to optimally select and size a polygeneration system supplying electricity, heat, cold and fresh water demands. They considered natural gas, solar energy and gasified biomass as energy sources and two technologies of RO and MED for fresh water production unit. The model optimised three criteria of economic, energy saving and GHG emissions. In another study, Bilton and Kelley [67] also proposed the best configuration and size of an integrated RO desalination unit and a hybrid energy system with battery storage. They employed a GA coupled with both simulation and cost models to determine design variables with minimum lifecycle cost.

Finally, several studies have focused on the application of optimisation techniques to modify or design desalination processes and operational conditions considering low-grade heat and energy recovery as a base-line source of energy. For instance, Christ et al. [68] developed a thermodynamic-based optimisation model to modify the process of MED such that it can be compatible with sensible heat sources. They employed a generalised reduced gradient (GRG) method for solving a NLP model to maximise the production of the fresh water. Likewise, Almansoori and Saif [69] employed a MINLP model to determine the optimal osmosis process as well as the operational conditions of a multi-utility plant consisting of a RO and pressure retarded osmosis (PRO) systems. The applicability of the model was examined using several hypothetical case studies.

4. Centralised/decentralised system approaches in optimisation models of the water supply side of the nexus

Historically, water and energy systems have been implemented and managed to service communities as centralised systems. However, as a result of limited resources, population growth and environmental concerns, there is an emerging paradigm shift from centralised to decentralised and distributed system approaches. In both water and energy sectors, the concept of the decentralised vs. centralised system is derived from the idea of exploiting existing local resources and alleviation of utility-related environmental impacts [12, 88]. These two system approaches are mainly differentiated based on the diverse aspects of the scale (size), applied technologies, components of the system and distance from the source [89, 90]. Accordingly, centralised systems are employed more for larger scales such as cities, while decentralised systems are generally practiced in semi-urban, rural and remote areas where there is no access to centralised systems [88, 89, 91]. However, these latter systems can also supply the demand either independently or as a satellite of a centralised system within an urban environment [88, 89, 92].

Apart from studies covering water supply systems powered by fossil fuel energy sources**,** which have mainly addressed WDS as part of a centralised system, it seems virtually all optimisation models have been developed for remote areas, small communities and villages [43, 45, 54, 67] and only a few studies have been conducted in the scale of a household or cluster of households [31, 53]. This implies that there is a knowledge gap in the optimisation of the integrated decentralised water and energy systems independently or as an integral part of a centralised system for different levels of scale in an urban context (satellite systems). This is consistent with Retamal et al. [93] who emphasised the importance of city-based studies for energy intensity analysis of water supply systems.

Furthermore, as mentioned in Section 3, optimisation problems of water supply side of the nexus including decentralised systems have been addressed from either water or energy point of view, while there is a variation in both terminology and definition of different levels of decentralisation, even within each of these two sectors [12, 89]. The lack of unified language, jointly used for the decentralised system approach in water and energy sectors may result in a degree of confusion when it comes to describing system models and spatial analysis of the problems in water supply side of the nexus. It also highlights the fact that only through the determination of key aspects of the integrated decentralised water and energy system, is it possible to reach a clear definition for different spatial scales and related water and energy system components.

5. The role of uncertainty in optimisation models of the water supply side of the nexus

Quantifying uncertainties in optimisation problems results in more reliable models which can assist in evaluating short and long-term implications of uncontrolled factors on system performance. In water supply systems, uncertainties are mainly caused by population growth projections, types of dwelling people live in, pattern of water use, water efficiency of households or businesses, price and climate change [94]. However, for systems fuelled by renewable energies, the intermittent nature of these sources adds to the degree of uncertainty.

Compared to deterministic models [21, 35, 44, 60], there are far less studies in the water supply side of the nexus considering uncertainties in optimisation models. Zhang et al. [38] developed a multi-objective two-stage stochastic integer optimisation model for the energy-effective design of a reclaimed water network with respect to the uncertainty associated with reclaimed water demand. In integration with renewable energy systems, Kyriakarakos et al. [43] integrated TRNSYS simulation with PSO to optimally design a renewable-based polygeneration system. Using monte carlo simulation (MCS) technique, they considered the uncertainties regarding the prices of fuel and electrochemical components as well as interest rate. Recently, Al-Nory and Brodsky [60] have also addressed the uncertainties regarding renewable energy supply as well as water and electricity demands in optimising integrated water supply and hybrid energy systems. They applied a LP model considering Gaussian random variable to optimally schedule the production and storage of the desalinated water integrated with a grid-connected renewable energy system.

Generally, the main problem of modelling uncertainty is the necessity of limiting a set of probable scenarios to avoid the computational difficulties. The process of creating a representative set of scenarios especially in cases where the degree of uncertainty is high may adversely affect the reliability of the solutions [95]. However, there are very few studies in the water supply side of the nexus addressing this issue. For instance, Goryashko and

Nemirovski [95] employed robust counterpart approach to minimise the energy cost of the daily operation of a WDS while taking into account uncertainty regarding water demand.

Accordingly, there is still a major gap exists in modelling the uncertainty such that it not only avoids highly complex numerical process, but also is the most representative of variations in the real world.

6. Future directions

Employing renewable energies as part of a hybrid energy system for water supply systems has become a promising research area. This is mainly due to increasing concerns regarding the growing water-related energy demand, the unsustainability of the fossil fuel energy sources and related environmental impacts.

While most of the studies in this respect have been conducted at the scale of small communities in remote areas, there is a growing need to look into feasibility and implication of applying such systems at different levels of scale within cities. Water supply to metropolitan areas is becoming more challenging as a result of rapid urbanisation growth worldwide [96]. At present, cities accommodate more than 50% of the global population which is predicted to increase to 67% by 2050 [97]. This creates a situation where cities are responsible for the majority of resource consumption and GHG emissions [98]. In fact, not only are the issue of limited water resources and increasing demand the primary concerns of urban water suppliers, but also providing the energy required for water supply systems and related environmental impacts.

Although the necessity of using renewable energies for urban water supply system has been recognised, fossil fuels by far are still the most predominant energy source in the water-related energy mix. This is mainly due to the lack of knowledge to predict implications of applying renewable energy in the urban water supply as well as high level of complexity at both technical and planning levels to implement such systems. Therefore, future research needs to focus on developing interpretable models for associated techno-economic feasibility evaluation and then for optimising an urban water supply system compatible with such hybrid energy system. In this regard, site-specific renewable energy characteristics within the urban environment play an important role.

We anticipate that the future research will focus on cities located in arid and semi-arid areas; where energy-intensive drought-proof technologies, such as recycling systems and desalination, need to be applied to offset water shortages. However, these metropolitan areas enjoy profuse solar energy which potentially can highly contribute to the water-related energy mix.

Currently, solar energy in urban areas is mostly captured through grid-connected rooftop PVs in residential buildings to meet household energy demand, often with self-sufficiency and low-carbon development as an objective. However, high penetration of PVs to existing electrical grids is constrained due to several technical and management issues they may cause in the power distribution network[1] [99-101]. These issues are mainly associated with the intermittent nature of the solar irradiance and the mismatch between the time of the energy production and the load demand leading to supply surplus PV output back to the electrical grid.

A potential solution to the above problem can be urban water supply systems powered by hybrid energy sources consisting of both grid electricity and surplus PV generation fed into the distribution network. These systems may also be integrated with different energy storage alternatives which not only results in exploiting the renewable energy, but also mitigates the adverse effects of inconsistency between energy demand and supply on the electrical grid. In addition, such integrated water and energy systems, will open a new avenue of study on planning, design and operation of the urban water supply system, which guarantees the reliability and sustainability of the future supply systems and assists decision makers and stakeholders to adopt short and long term economical approaches in both water and energy sectors. Therefore, the major future direction of studies in this area is projected to be system boundaries definition, feasibility evaluation and development of optimisation frameworks that address different parameter uncertainties by exploring dynamic relationships between related causes and applying prediction models.

7. Conclusions

In this paper, we provided a detailed overview of optimisation techniques applied to problems in the water supply side of the water-energy nexus. We summarised the latest research developments in this area according to types of the energy sources, centralised/ decentralised system approaches and system parameters uncertainty.

The optimisation of problems in the water supply side of the nexus has been mainly addressed from either water or energy perspective and there is a lack of studies optimising the

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[1] The main electricity transmission issues caused by grid-connected rooftop PVs includes: Voltage rise, Reactive power generation and System Harmonics [99]. Further discussion of these issues is beyond the scope of this paper.

system holistically. Furthermore, nearly all studies related to water supply systems fuelled by renewable or hybrid energy sources, have addressed design and operation aspects of the system and to the best of our knowledge there is not an optimisation framework for long-term planning purposes. This is identified as a major gap given the urgency of the expansion and retrofitting of current infrastructures in water supply systems compatible with potential energy sources, while taking into account spatial considerations and environmental impacts.

We also looked into optimisation models from the centralised and decentralised systems perspective. In this regard, most of the optimisation models in water supply side of the nexus have been developed for remote regions and small villages and there is a lack of studies in other decentralised levels and also centralised system scales. However, of different scales of studies, the absence of city- based studies is identified as an important gap. This is mainly due to the key role of the cities in conserving water and energy resources and their impacts on policy making in both local and national levels. A lack of unified language, jointly used for the decentralised system approach in water and energy sectors is known as one of the obstacles to precisely define and develop system models for different scales.

It is also recognised that nearly all the studies have ignored uncertainties in different parameters of the optimisation models. Considering the impact of these uncertainties would assist with better understanding of the systems under real conditions.

Finally, based on the identified knowledge gaps, we expect that future studies will be more focused on optimising urban water supply systems driven by hybrid energy sources including grid-connected rooftop PVs and grid electricity.

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Foreword to Chapter 2

In Chapter 1, the existing optimisation studies in water supply side of the nexus from three different aspects of the system energy sources, centralised or decentralised approaches and system parameters uncertainties were reviewed and the following knowledge gaps were identified:

1. Lack of spatial long-term optimisation planning models for urban water supply systems considering the energy aspect of the problem
2. Absence of studies investigating the effect of parameters uncertainties on the optimal solutions of the problems defined in water supply side of the nexus
3. Lack of optimisation models in water supply side of the nexus considering the interaction of water and energy supply simultaneously
4. Lack of studies evaluating the effect of the environmental aspects of the optimisation problems in water supply side of the nexus by considering them in the formulation of the optimisation model

Accordingly, given the current issues facing urban water and energy supply, it was suggested that developing optimisation models for design, operation, and planning of a desalination-based water supply system driven by grid electricity and surplus PV output (hybrid energy sources) is a potential future direction of research through which the existing knowledge gaps can be filled. However, it is crucial to investigate if it is worthwhile (from economic and PV installation capacity points of view) to consider surplus PV output as a part of water-related energy mix. According, in Chapter 2, a mathematical optimisation model is developed for the optimal operation of a desalination-based water supply system driven by hybrid energy sources and the results are compared with a scenario where grid electricity is a sole energy source.

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Chapter 2- Water security and clean energy, co-benefits of an integrated water and energy management

This chapter has been presented at the oral platform in 27th European Symposium on Computer Aided Process Engineering (ESCAPE 27), and published as a chapter in the book series of Computer-Aided Chemical Engineering.

Reference

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The formatted published paper is presented in Appendix 2, Section A2.2.

Authors contribution

Contributor	Statement of contribution	Signature
Negar Vakilifard*	All the literature review, optimisation modelling, simulation, data collecting, and analysis, designing of the scenarios, writing the manuscript and revising it based on the received feedbacks	
Parisa A. Bahri	Critical review of the paper, technical advice on the design of the scenarios giving feedback on the draft and principal supervisor of the project	
Martin Anda	Peer review of the paper and co-supervisor of the project	
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Abstract

Considering daily surplus output from grid-connected rooftop photovoltaics (PVs) as part of an urban water-related energy mix, this can incentivise the connection of higher number of PVs to the existing grid networks. It has also the benefit of delivering sustainability to energy-intensive water supply technologies such as desalination in cities located in dry climate regions. In this paper, we describe an optimal operation of a desalination-based urban water supply system driven by both grid electricity and surplus PV output. Three tools of geographical information system, system advisor model and Excel are integrated to support a linear programming model. The model is solved through a two-step optimisation approach taking into account water and energy demand and supply systems as well as time of use electricity tariffs. The optimum solution for the north-western corridor of Perth, Australia, shows 12.1 % total cost reduction per day for water supplier and 123 % increase in PV installation capacity; resulting in great benefits for both water and energy sectors.

Keywords: Desalination, Rooftop photovoltaics, Optimisation, Water supply

1. Introduction

In cities located in areas enjoying profuse solar irradiance, grid-connected rooftop photovoltaics (PVs) is a promising option to generate clean energy (Ruhang, 2016). However, the installation density of these systems is generally limited to the hosting capacity of the existing grid network to deal with the intermittency of surplus PV output fed into the grid as a result of the mismatch between load and electricity supply.

In the context of integrated water and energy management, this issue can be addressed by considering desalination plants as a deferrable load to create compatibility between load and supplied electricity. The extra water produced can be stored for later use or reticulated to other parts of the water network. The approach also benefits the water sector, since desalination, as an energy intensive technology, can thereafter be considered as a sustainable alternative for urban water supply.

Al-Nory and El-Beltagy (2014) for the first time proposed a model for optimal scheduling of water production and storage of centralised desalination plants integrated with smart grid to combat the intermittency of connected renewable energy sources. However, the model has been developed at national scale in which the complexities of water and energy system configurations are generally ignored. It has also considered a centralised authority for both water and energy supply that naturally eliminates the interaction between the two sides involved. In this paper, we address these limitations by developing a linear programming (LP) model for optimal operation of a desalination-based water supply system in urban areas while considering electricity cost tariffs to bridge between water and energy sectors. In addition, to the best of our knowledge, this is the first time that the effect of integrating daily surplus PV output with existing grid electricity on optimal operation of an urban water supply system is investigated, taking into account the spatial and temporal characteristics of water and energy systems. The proposed model is applied to the north-western corridor of Perth, the largest desalinated water consumer in Australia (Shahabi et al., 2015).

2. Methodology

2.1. Spatial and temporal analysis

Applying ArcGIS 10 integrated with Excel, we determined four clusters in the studied area, based on local government area (LGA) and associated population data (Australian Bureau of Statistics, 2016) as well as zone substations' service area. The geographical information system (GIS) data for zone substations' service area was obtained from Western Power, the main WA's electricity supplier. We also considered four daily time blocks of "low", "morning peak (M-P)", "medium (Med)" and "evening peak (E-P)" based on Perth's diurnal water demand for two seasons of "summer (S)" and "winter (W)" in the planning horizon of the year, 2016. For the rest of the paper, we use the term "time period" for the whole mentioned time expression, except for cases where different time periods need to be pointed out specifically.

2.2. Water demand and supply system

We assumed total water demand in the area is met by a decentralised seawater reverse osmosis (SWRO) desalination water supply system consisting of pumping system and storage tanks (Figure 1). Using a simple unit loading method (Walski et al., 2003) to forecast water demand at the end of 25 years (useful lifetime of the plant), the annual average capacity of each desalination plant was ascertained considering the capacity factor of 0.85. In each cluster, the maximum capacity of the storage tank and minimum allowable stored water was determined such that it can meet 2-day and 2-hour average daily water demand, respectively. The initial stored water was assumed to be equal to its minimum allowable. The capacity of the plants and storage tanks in each cluster are tabulated in Table 1.

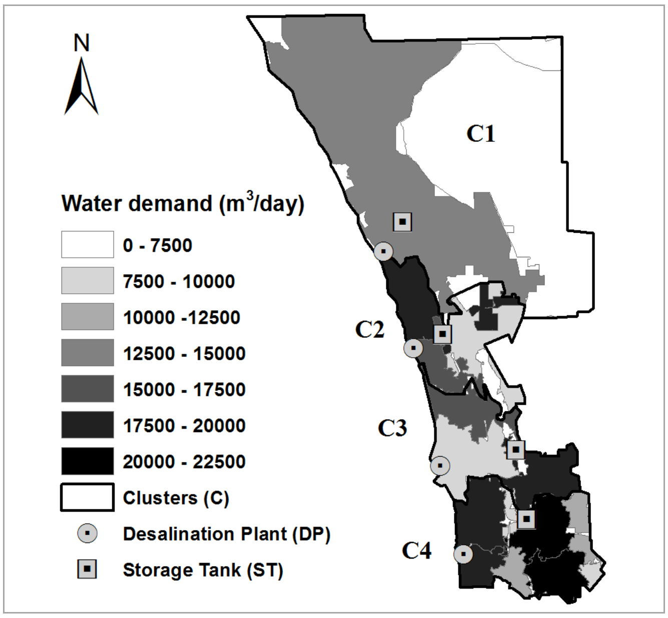


Figure 1: Clusters boundaries, locations of DPs and STs and spatial distribution of average water demand in 2016

Table 1: Capacities of desalination plants (DP) and storage tanks (ST) in each cluster (C)

Clusters	DP capacity (m^3 /day)	ST capacity (m^3)
C1	17,000	16,000
C2	68,000	60,000
C3	67,000	60,000
C4	200,000	180,000

2.3. Energy demand and supply system

Both residential and water-related energy demand were taken into account considering that nearly the whole studied area is covered by households. To determine the residential electricity demand, the index of the average annual hourly electricity consumption per capita was defined based on substations' annual hourly electricity data in the studied area and the number of connected households. The associated data was obtained from Western Power. In regards to water-related energy demand, we considered the average value of 4 kWh/m^3 (Ghobeity and Mitsos, 2014) as specific energy consumption of all desalination plants. The specific energy requirement of water pumping was also calculated for each cluster with the same assumptions as previous study conducted by Shahabi et al. (2015).

We determined the maximum grid electricity that can be transferred to each cluster based on the substation transformers' ratings data obtained from Horizon Power (2015). In addition, we considered the commonly used 4 kW PV system as the only PV system size installed in the studied area and determined its performance using system advisor model (SAM 2016.3.14) integrated with Excel analysis.

2.4. Cost data

The residential and water-related energy price data were adopted from regulated time of use (TOU) electricity tariffs for residential and business sectors, respectively (Synergy, 2016a). To determine the cost data for surplus PV output usage, we used the net feed-in tariff (Synergy, 2016b) currently implemented by power supplier to buy residential PV output sent back to the grid. We also obtained $\$0.39/m^3$ for the operational and maintenance costs (O&M) of desalination plants (excluding electricity costs), based on the data collected from literature (Voutchkov, 2012). Fixed water storage cost of \$138 per thousand m^3 was also adopted from Al-Nory and El-Beltagy (2014). All prices were converted into 2016 Australian dollar, using the exchange rate of 0.7236 (RBA, 2017).

2.5. Mathematical formulation

The problem was formulated as a LP model through a two-step optimisation approach. In the first step, the optimal allocation of each energy source (grid electricity and PV output) to residential demand was determined such that the total energy cost for householders is minimised. The outcome of the first- step of the optimisation was stored in an auxiliary parameter which was then used in the second-step, as a new constraint to determine the remaining capacity of each energy source. In the second-step, maximum exploitation of surplus PV output to supply water-related energy demand was achieved by minimising the total cost for water supplier including energy costs, O&M costs of desalination plants and storage costs. The objective functions (z1 and z2) and model constraints (Eqs. (1)-(16)) are presented as follows:

$$z_1 : Min \sum_t \sum_i \sum_s \sum_b C^{er}_{t,s,b} * P^{r}_{t,i,s,b}$$

$$z_2 : Min \sum_t \sum_i \sum_s \sum_b (C^{rb}_t * RE^{w}_{t,i,s,b} + C^{eb}_{t,s,b} * P^{w}_{t,i,s,b} + C^{OM}_t * Q_{t,i,s,b} + C^{s}_t * V_{t,i,s,b})$$

Residential energy balance:

$$P^{r}_{t,i,s,b} + RE^{r}_{t,i,s,b} = D^{er}_{t,i,s,b} \tag{1}$$

Max. residential PV share:

$$RE^{r}_{t,i,s,b} \leq k1 * D^{er}_{t,i,s,b} \tag{2}$$

Water-related energy balance:

$$P^{w}_{t,i,s,b} + RE^{w}_{t,i,s,b} = Q_{t,i,s,b} * Dep_{t,i} + WP_{t,i,s,b} * Des_{t,i} \tag{3}$$

Total and Max. grid share:

$$P_{t,i,s,b} = P^{r}_{t,i,s,b} + P^{w}_{t,i,s,b} \tag{4}$$

$$P_{t,i,s,b} \leq dur_b * MaxPS_{t,i} \tag{5}$$

Total and Max. PV share:

$$RE_{t,i,s,b} = RE^{r}_{t,i,s,b} + RE^{w}_{t,i,s,b} \tag{6}$$

$$RE_{t,i,s,b} \leq MaxR_{t,i,s,b} \tag{7}$$

Unused surplus PV output:

$$RE^{rem}_{t,i,s,b} = MaxR_{t,i,s,b} - RE_{t,i,s,b} \tag{8}$$

Water balance:

$$WQ_{t,i,s,b} + WV_{t,i,s,b} = D^{w}_{t,i,s,b} \tag{9}$$

Max. water distributed directly from the plant:

$$WQ_{t,i,s,b} \le Q_{t,i,s,b} \tag{10}$$

Max. water distributed from the storage tank:

$$WV_{t,i,s,b} \le V^{0}_{t,i,b} + V_{t,i,s,b-1} \tag{11}$$

Max. water desalinated:

$$Q_{t,i,s,b} \le dur_b * convf * MaxA_{t,i} \tag{12}$$

Min. water desalinated:

$$Q_{t,i,s,b} \ge dur_b * convf * MinQ_{t,i} \tag{13}$$

Water pushed for storage:

$$WP_{t,i,s,b} = Q_{t,i,s,b} - WQ_{t,i,s,b} \tag{14}$$

Total water stored:

$$V_{t,i,s,b} = V_{t,i,s,b-1} - WV_{t,i,s,b} + WP_{t,i,s,b} \tag{15}$$

Water storage bound:

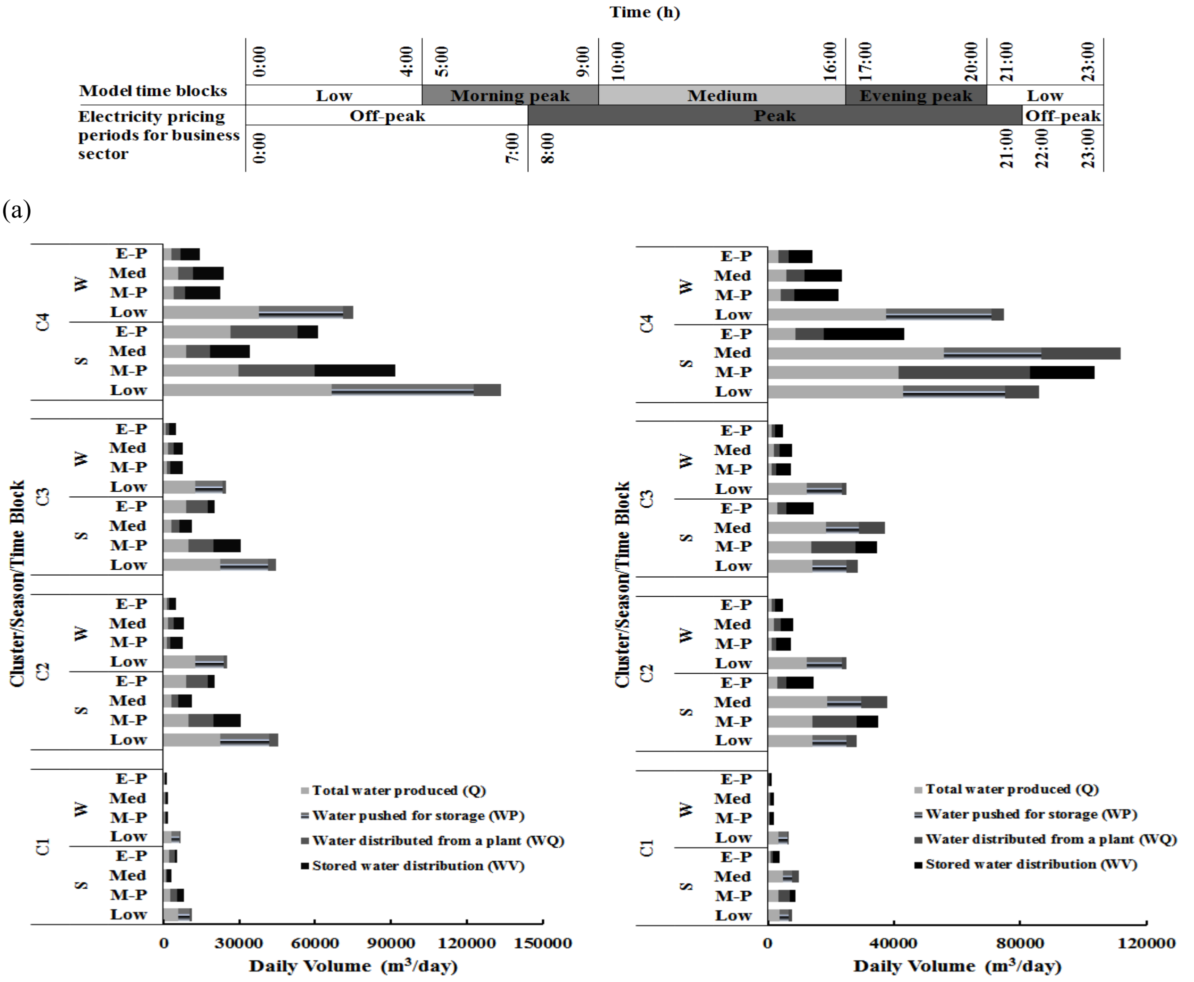
$$MinS_{t,i} \le V_{t,i,s,b} \le MaxS_{t,i} \tag{16}$$

3. Results and discussion

The LP model was coded into GAMS 24.3.1 software and solved by CPLEX 12.6. The optimum solution was first obtained for the "base scenario" where grid electricity is the only energy source that can be assigned to water-related energy demand. In the next step, the model was solved for the "hybrid energy scenario" where water-related energy demand can be met by both grid electricity and surplus PV output. From a modelling point of view, this means that the maximum PV installation capacity should be constrained to avoid surplus PV output to the electrical grid.

As shown in Figure 2(a) and 2(b), in base scenario, the operation scheduling in all clusters basically follows the TOU tariff periods for business sector. Accordingly, the maximum water production and storage occur in water low demand time block coinciding with off-peak electricity period. In summer, the amount of water assigned to the demand from the storage tanks has the largest share of water supply, around 64 %, in medium water demand time block corresponding to the peak electricity rate. In winter time, on the other hand, the proportion of water demand satisfied by the stored water is larger than summer, at highest

77% in morning peak water demand time block followed by the average of 68 % in medium and evening peak water demand periods. This is due to the lower daily water demand during winter leading to retention of more water in storage in each time block for later use. The outcome of the model for base scenario resulted in the total cost of $258,103/day for operating desalination-based water supply. In the hybrid energy scenario (Figure 2(c)), the optimum operation is affected by both availability of PV electricity and TOU tariff for business sector. During summer, a large amount of desalinated water is produced and stored in the low water demand time block concurrent with off-peak electricity period. However, despite the peak electricity rate, the highest production occurs in the medium water demand time block in which surplus PV output is available to be allocated to the water-related electricity demand. Moreover, in contrast to the base scenario, in summer, all water demand during medium time block is met by desalinated water directly distributed from desalination plant. This is due to the availability of renewable energy during this time block to provide water-related energy demand. Thus, more water remains in the storage tank for the next time block when there is no PV generation but still within the peak electricity period. The outcome of the model for winter time is similar to those for the base scenario, where the system operation follows TOU tariff for the business sector. This is because of the lack of sufficient PV generation during winter in order to compensate peak electricity rates during medium water demand time block. Finally, compared to the base scenario, the optimal solution for the hybrid energy scenario leads to average of 12.1 % total cost reduction per day and up to 123 % rise in PV installation capacity in the studied area which is a considerable increase.



(a)

(b)

(c)

Figure 2: (a) Model time blocks vs electricity pricing periods for business sector; Optimum desalination-based water supply system: (b) Base scenario (c) Hybrid energy scenario

4. Conclusions

In this paper, we presented a LP model for optimal operation scheduling of an urban desalination-based water supply system which has the most compatibility with available surplus PV output and demonstrated its application and advantages for the north-western corridor of Perth, Australia. Based on the results, the proposed model benefits both water and energy sector through providing cost effective sustainable water supply and increasing the share of renewable energy in the total urban energy mix.

Nomenclatures

Sets

t = planning horizon

s = season

b = time block

i = cluster

Model parameters

$C^{er}_{t,s,b}$ = residential electricity cost (\$/kWh)

$C^{eb}_{t,s,b}$, C^{rb}_{t} = water supply energy costs (\$/kWh)

C^{OM}_{t} = O&M cost of a plant (\$/m^3)

C^{s}_{t} = storage cost (\$/m^3)

$convf$ = conversion factor (day/h)

$D^{er}_{t,i,s,b}$ = residential energy demand (kWh)

$D^{w}_{t,i,s,b}$ = water demand (m^3)

$Dep_{t,i}$ = plant specific energy (kWh/m^3)

$Des_{t,i}$ = pumping specific energy (kWh/m^3)

dur_{b} = duration of the time block (h)

$k1$ = installation density (%)

$MaxA_{t,i}$ = Max. plant capacity (m^3/day)

$MaxPS_{t,i}$ = Max. substation capacity (kW)

$MaxR_{t,i,s,b}$ = Max. PV output (kWh)

$MaxS_{t,i}$ = Max. storage tank capacity (m^3)

$MinQ_{t,i}$ = Min. plant production (m^3/day)

$MinS_{t,i}$ = Min. allowable stored water (m^3)

$V^{0}_{t,i,b}$ = initial stored water (m^3)

Decision variables

$P^{r}_{t,i,s,b}$ = grid share for residents (kWh)

$P^{w}_{t,i,s,b}$ = grid share for water supply (kWh)

$P_{t,i,s,b}$ = total grid share (kWh)

$Q_{t,i,s,b}$ = total water produced (m^3)

$RE^{r}_{t,i,s,b}$ = PV share for residents (kWh)

$RE^{w}_{t,i,s,b}$ = PV share for water supply (kWh)

$RE_{t,i,s,b}$ = total PV share (kWh)

$V_{t,i,s,b}$ = total water stored (m^3)

$V_{t,i,s,b-1}$ = total water stored in prior time block (m^3)

$WP_{t,i,s,b}$ = water pushed for storage (m^3)

$WQ_{t,i,s,b}$ =water distributed from a plant (m^3)

$WV_{t,i,s,b}$ = stored water distribution (m^3)

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Foreword to Chapter 3

In Chapter 2, the optimal operation of an urban desalination-based water supply system was addressed within the context of integrated water and energy management. It was shown that considering surplus PV output as part of the water-related energy mix results in better economic performance and higher level of PV installation capacity[1], in comparison with the case where grid electricity is the only energy source. In both scenarios, desalinated water production and storage can vary in different time blocks of a representative day in each season of summer and winter. This operational scheduling, however, is not the operational mode commonly implemented in the existing desalination plants. Thus, in Chapter 3, the model is extended to explore in detail the effect of adopting hourly basis mode of operation versus currently executed seasonal and yearly basis operational scheduling on both optimal investment and operational decisions of the desalinated-based water supply system driven by hybrid energy sources.

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[1] PV installation capacity (density) is defined as the number of households equipped with PV systems in each zone divided by the total number of households in the same zone

Chapter 3- A two-level decision making approach for optimal integrated urban water and energy management

This chapter has been published in the journal of Energy as a research paper.

Reference

Vakilifard N, A. Bahri P, Anda M, Ho G. A two-level decision making approach for optimal integrated urban water and energy management. Energy. 2018;155:408-425.

The formatted published paper is presented in Appendix 2, Section A2.3.

Authors contribution

Contributor	**Statement of contribution**	**Signature**
Negar Vakilifard*	All the literature review, design of the optimisation framework, all mathematical modelling, simulations, designing of the scenarios, data collecting and analysis, writing the manuscript, and revising it based on the received feedbacks	
Parisa A. Bahri	Critical review of the paper especially on the mathematical modelling and structure of the paper and giving feedbacks accordingly. Technical advice on designing the scenarios and sensitivity analysis, and principal supervisor of the project	
Martin Anda	Peer review of the paper and co-supervisor of the project	
Goen Ho	Peer review of the paper, giving feedback on the draft and co-supervisor of the project	

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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 to 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 regard, 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^s_t (\$/m^3)) is considered.

v) The amount of produced water that can be transferred between any two allowable zones ($L^w_{i,j}$) 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.

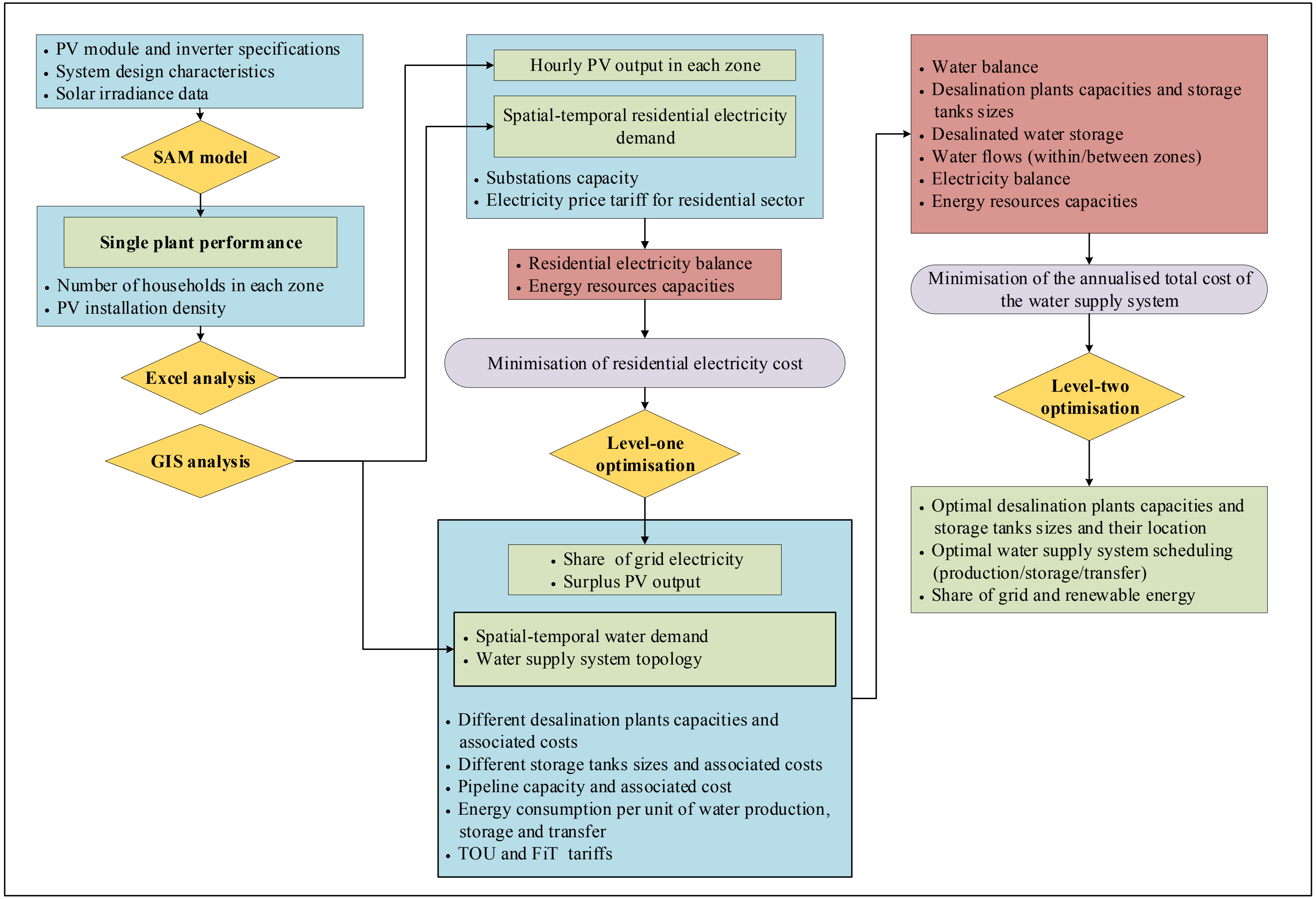

Fig. 1- Depiction of proposed two-level optimisation model

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):

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

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)):

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

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

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

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):

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

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):

$$CCDQ = \sum_{t}\sum_{i}\sum_{c} CapDQ_{c}.XW_{t,i,c} \tag{6}$$

$$CCSN = \sum_{t}\sum_{i}\sum_{m} CapSN_{m}.X_{t,i,m} + \sum_{t}\sum_{i}\sum_{j} CapWT.YY_{t,i}.L_{i,j}.convf_{2} \qquad \forall (i,j) \in \{L^{w}_{i,j} \big| i = j\} \tag{7}$$

$$CCWT = \sum_{t}\sum_{i}\sum_{j} CapWT.SY_{t,i,j}.L_{i,j}.convf_{2} \qquad \forall (i,j) \in \{L^{w}_{i,j} \big| i \neq j\} \tag{8}$$

  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):

$$FOC_t = \sum_{s} C_t^{feb}.nd_s \qquad \forall t \tag{12}$$

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:

$$\sum_{c} XW_{t,i,c} \leq 1 \qquad \forall t,i \tag{15}$$

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

$$\sum_{s} nd_s.\sum_{b} Q_{t,i,s,b} \leq PF.\sum_{s} DQ_{t,i}.nd_s \qquad \forall t,i \tag{16}$$

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)):

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

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:

$$\sum_{m} X_{t,i,m} \le \sum_{c} XW_{t,i,c} \qquad \forall t, i \tag{18}$$

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)):

$$\sum_{i} SN_{t,i} \ge \sum_{i} MinS_{t,i} \qquad \forall t \tag{19}$$

$$\sum_{i} SN_{t,i} \le \sum_{i} MaxS_{t,i} \qquad \forall t \tag{20}$$

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)):

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

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

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)):

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

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)):

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

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)):

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

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

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)):

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

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):

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

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

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.

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

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):

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

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:

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

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

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

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)):

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

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)).

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

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

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 was not 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

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

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 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.

Table 1- Desalination plants design capacities and storage tanks sizes

Water supply component	**Size**
Desalination plant (m^3/day)	20,000
	40,000
	60,000
	80,000
	100,000
	120,000
	140,000
Storage tank (m^3)	5,000
	10,000
	20,000

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.

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

	Distance/pumping elevation (m)			
	Z1	Z2	Z3	Z4
Z1	4,451/8.91	10,922/-	-	-
Z2	13,602/27.99	3,073/2.94	16,787/9.79	-
Z3	-	17,955/1.76	8,894/8.61	14,572/13.52
Z4	-	-	16,835/3.97	8,882/8.88

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.

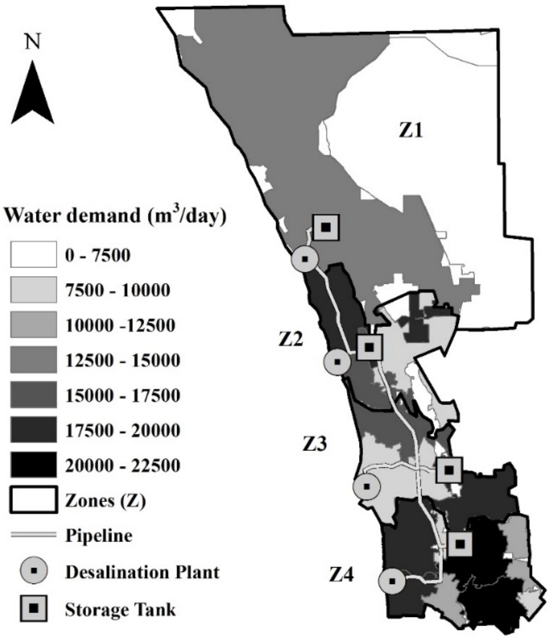

Fig. 2- Zones boundaries, possible locations for potential desalination plants, storage tanks and connecting pipelines, as well as spatial distribution of average annual water demand

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.

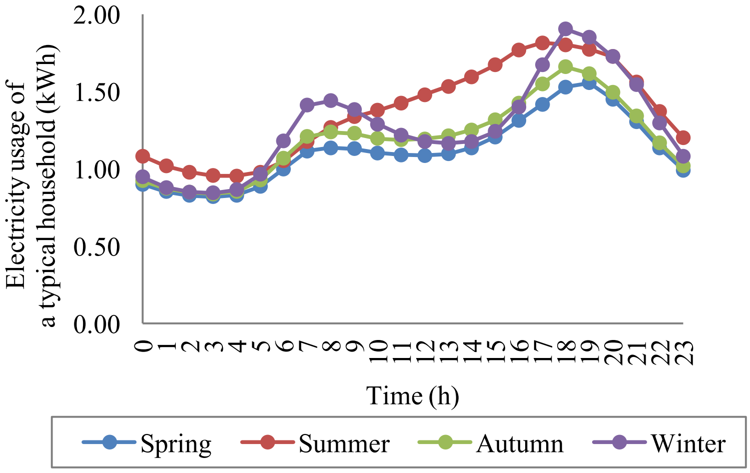

Fig. 3- The profile of the average hourly electricity usage of a typical household in the case-study area in each season

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.

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

	Z1	Z2	Z3	Z4
Zone substations capacity (kW)	76,000	152,000	190,000	494,000

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.

Table 4- SAM model input data

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]

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.

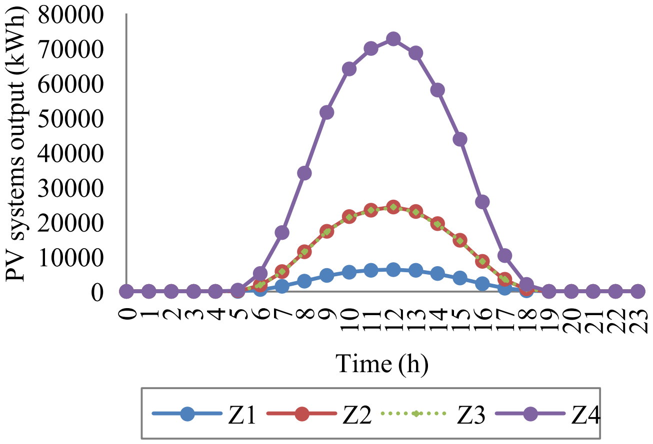

Fig. 4- Maximum PV systems output in each zone

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.

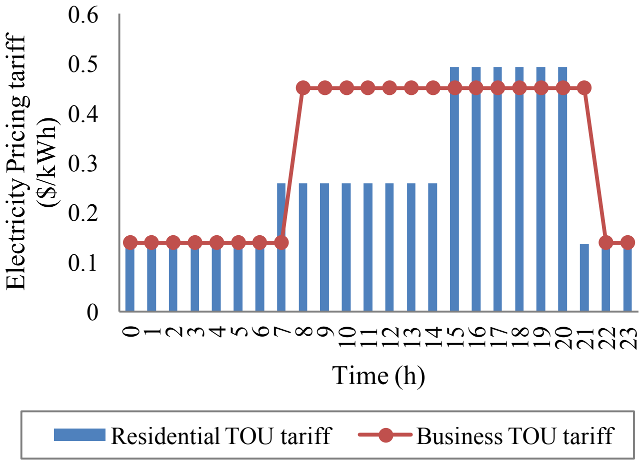

Fig. 5- Regulated TOU electricity tariffs for residential and business sectors implemented in the case-study

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.

Table 5- The model statistics for each scenario

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	12,943	9,691	9,065	626	13,660	11	-[1]
Semi-flexible	13,059	9,779	9,089	690	33,514	18	1.17E-08
Flexible	12,931	10,451	9,825	626	104,341	44	4.08E-02

[1] The problem was solved to the optimality

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 and therefore it is not demonstrable in Fig. 6.

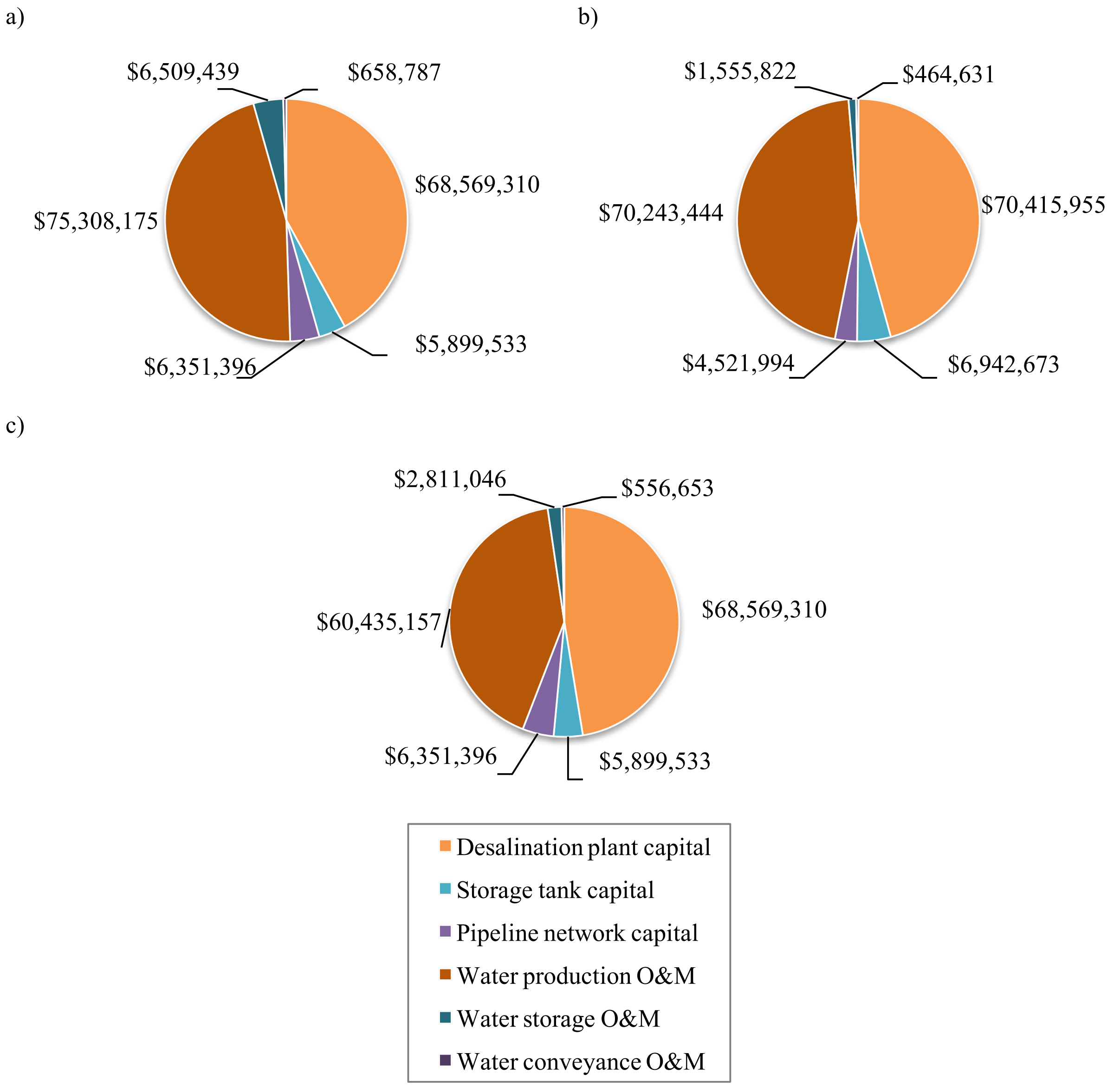

Fig. 6- Breakdown of the annualised total cost of the optimal desalination-based water supply system for three scenarios: a) Fixed b) Semi-flexible and c) Flexible

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.

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

	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(60,000) Z4(140,000)	Z1(20,000) Z2(40,000) Z4(140,000)	Z2(60,000) Z4(140,000)
Annual desalinated water production[2] (m^3)	Z2(18,615,000) Z4(43,435,000)	Z1(3,102,500) Z2(12,410,000) Z4(43,435,000)	Z2(14,587,010) Z4(43,435,000)
Storage location/ capacity (m^3)	Z2(10,000) Z4(5,000)	Z1(5,000) Z2(5,000) Z4(5,000)	Z2(5,000) Z4(10,000)
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

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.

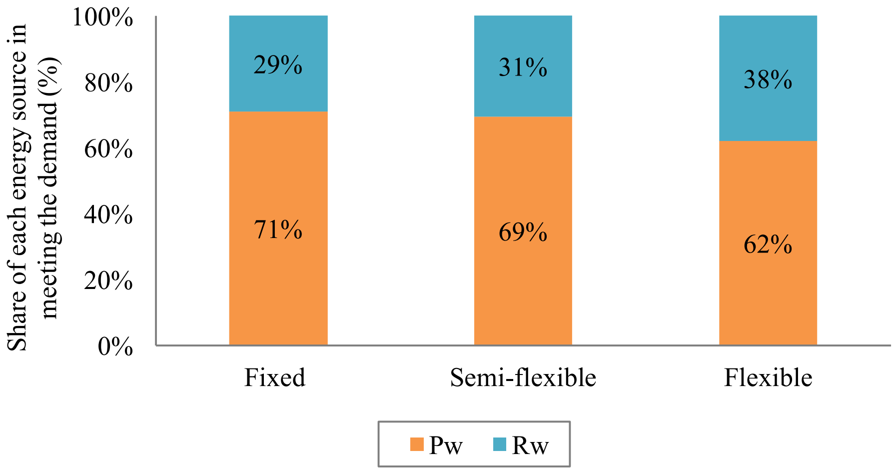

Fig. 7- Total share of surplus PV output (R^w) and grid electricity (P^w) in supplying water-related electricity demand

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 40,000 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 60,000 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.

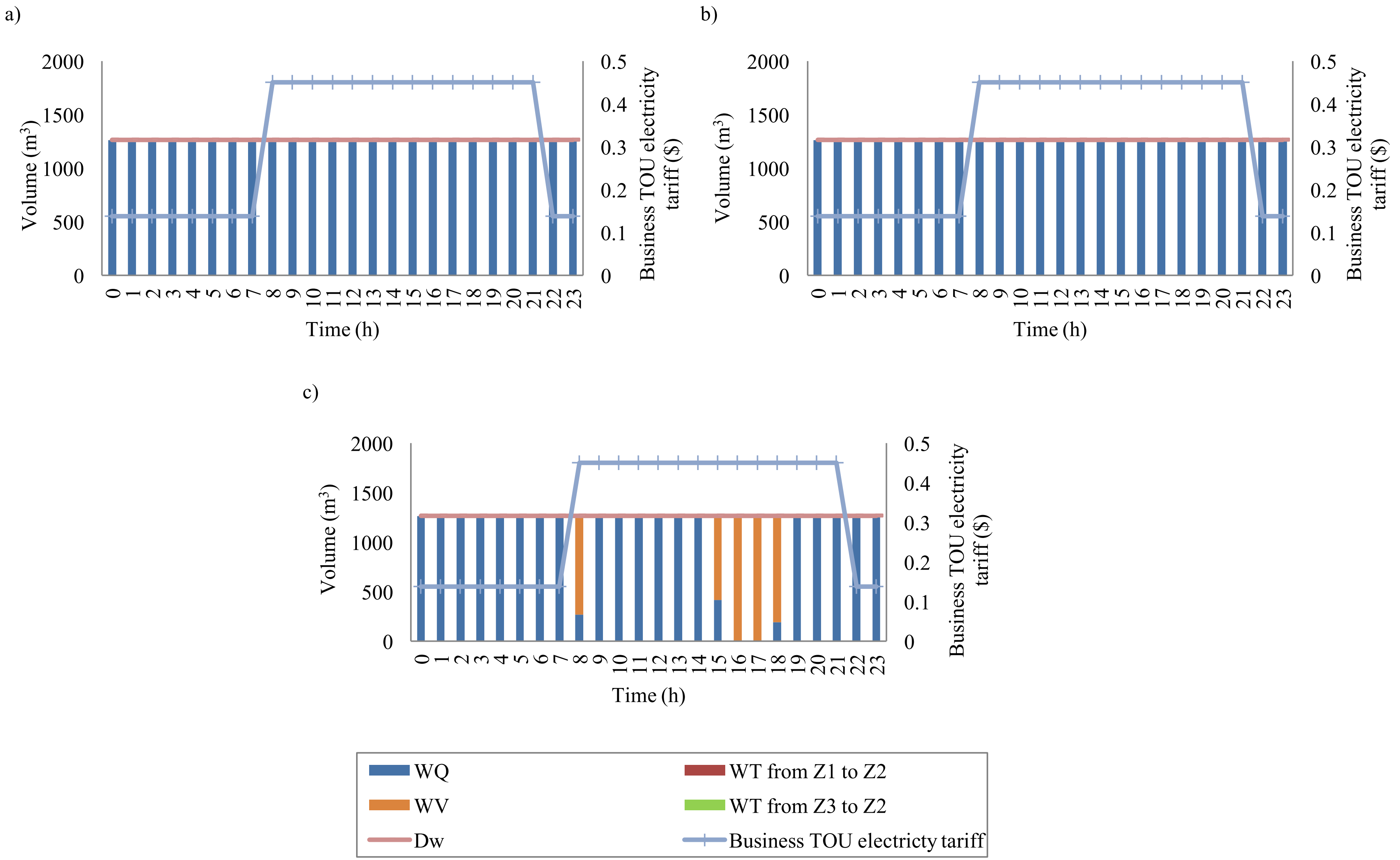

Fig. 8- Optimal water supply operation at the point of demand (D^w) in zone 2 during summer in three scenarios: a) Fixed b) Semi-flexible and c) Flexible, including water assigned directly from desalination plant (WQ), desalinated water transferred from other zones (WT) and desalinated water assigned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

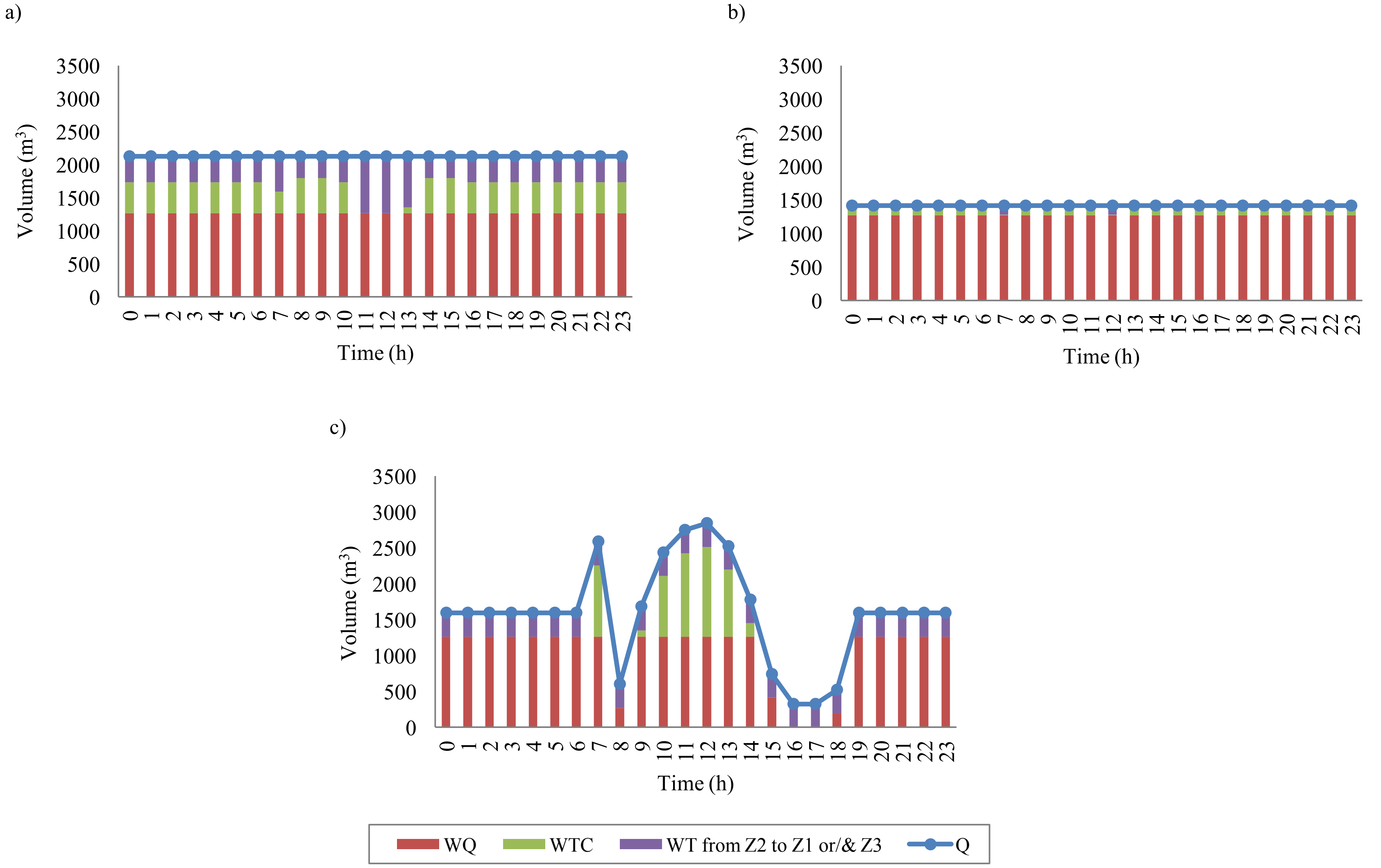

Fig. 9- Optimal water supply operation at the point of production in zone 2 during summer for three scenarios: a) Fixed b) Semi-flexible and c) Flexible, including water assigned directly from desalination plant (WQ), water pushed for storage from desalination plant (WTC), desalinated water transferred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

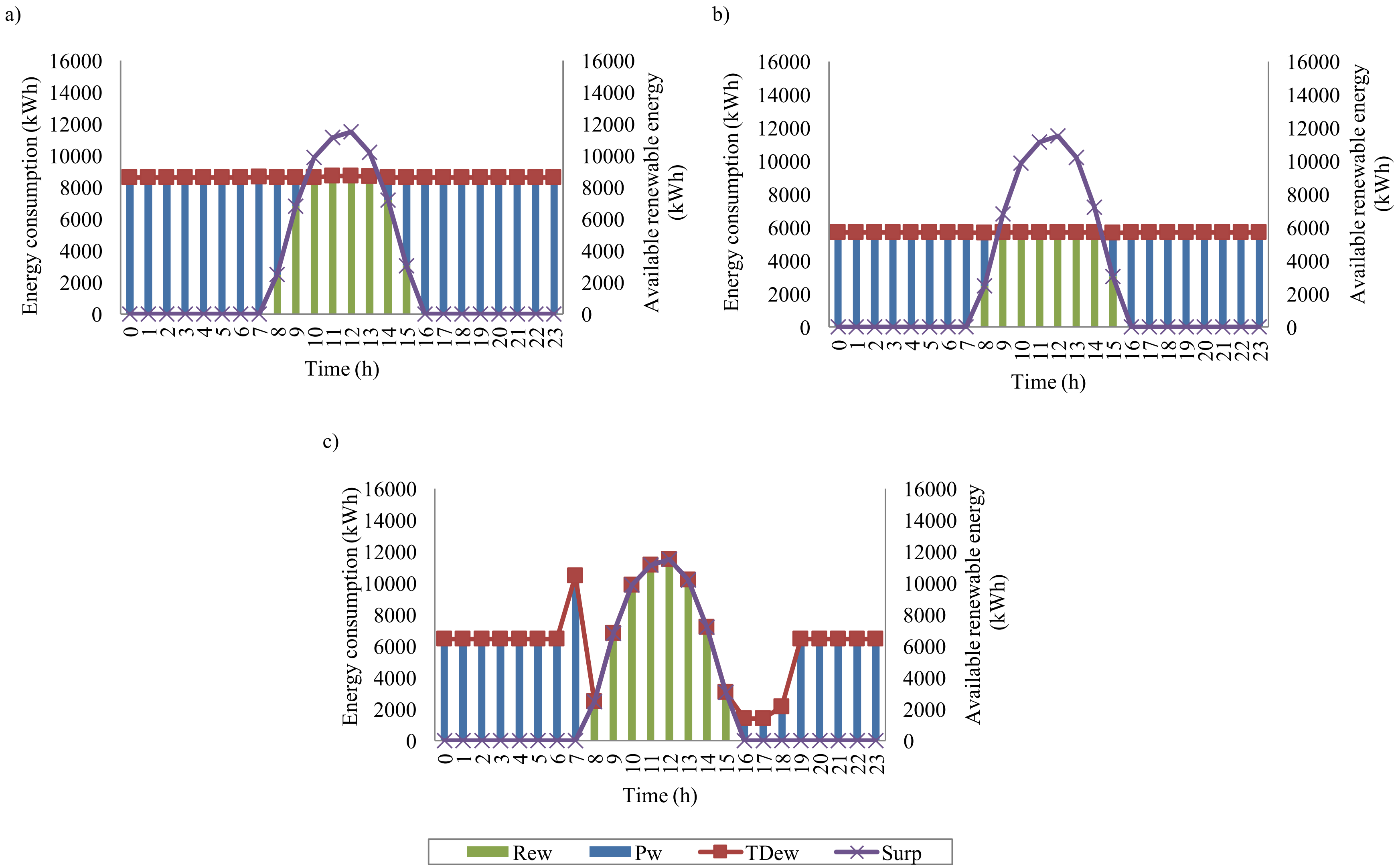

Fig. 10- Surplus PV output fed to the electrical grid (Surp) in zone 2 as well as optimal share of each energy source including surplus PV output (RE^{w}) and grid electricity (P^{w}) in meeting the total water-related energy demand (TD^{ew}) during summer for three scenarios: a) Fixed b) Semi-flexible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

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.

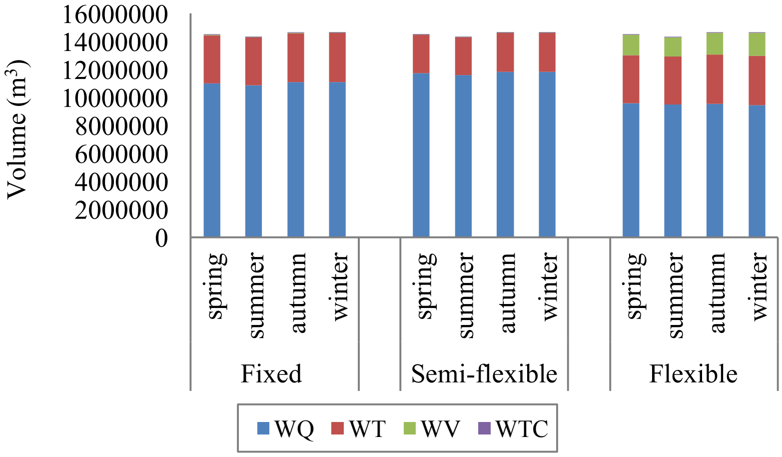

Fig. 11- The effect of seasonal changes on optimal operation of water supply system to meet the total water demand within case-study boundary during the one-year planning horizon

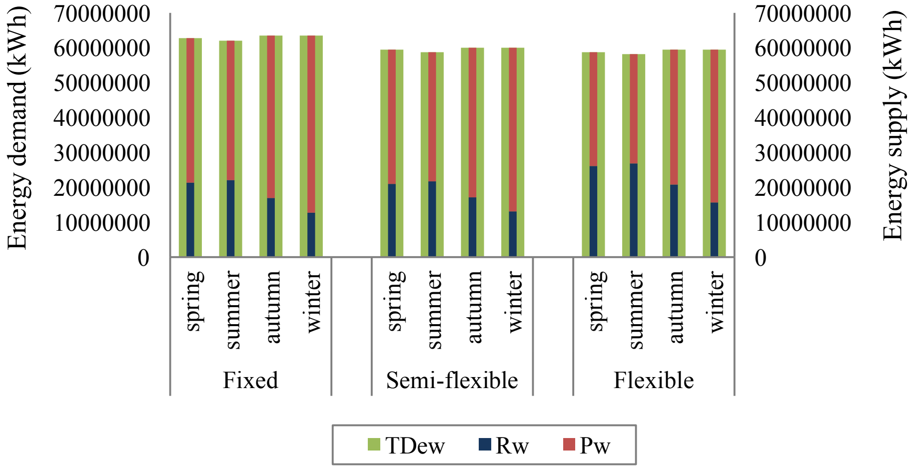

Fig. 12- The effect of seasonal changes on the share of energy sources to meet the total water-related energy demand within case-study boundary during the one-year planning horizon

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.

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

	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

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.

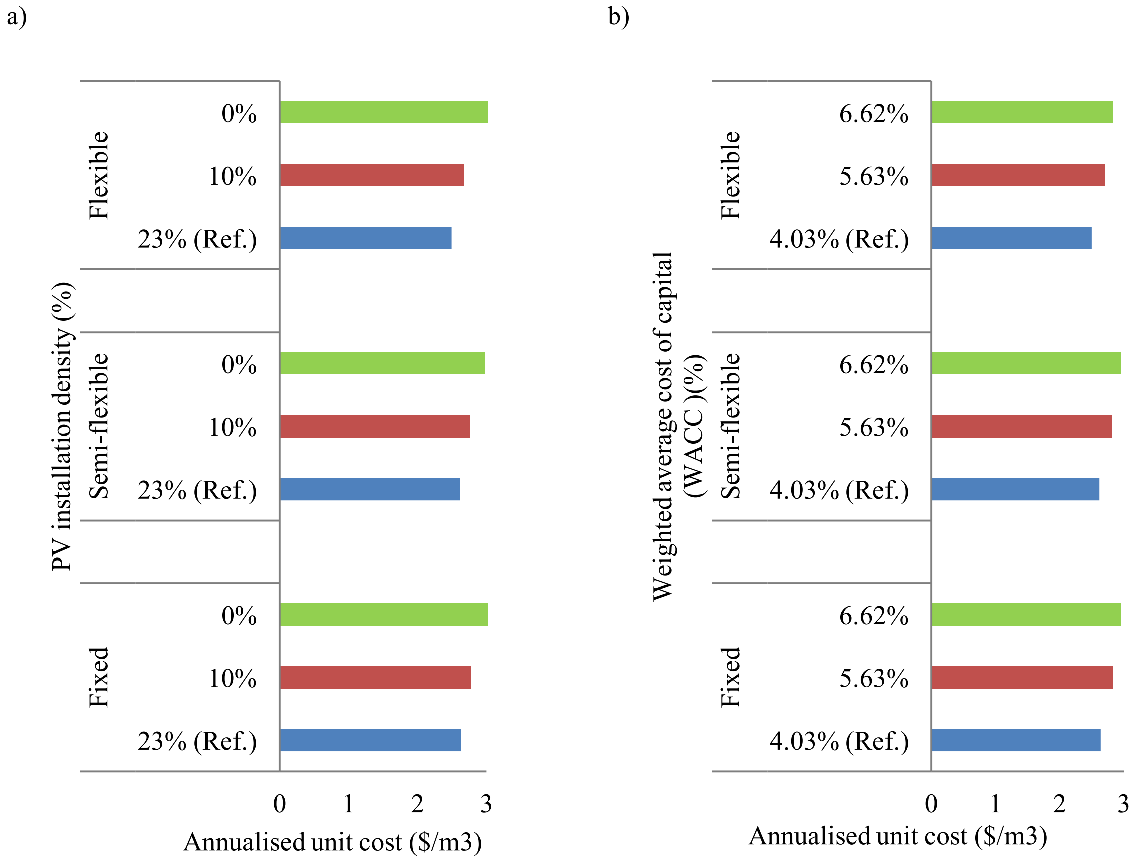

Fig. 13- Comparison of annualised unit cost of the optimal water supply system in fixed, semi-flexible and flexible scenarios: a) for three different PV installation densities and b) for three different financial rates

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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Foreword to Chapter 4

In Chapter 3, the effect of different operational scheduling, as well as seasonal change on the optimal decisions for the urban desalination-based water supply system driven by hybrid energy sources was investigated. The results indicated that compared to the existing desalination plant in Perth, considering renewable energy in driving water supply system has high economic benefit in terms of annualised unit cost of water production regardless of the operational mode. However, the detailed investigation on the effect of different operational modes on optimal investment and operational decisions showed that the flexible operational scheduling leads to the most compatibility with available renewable energy, higher share of renewable energy in water-related energy mix and better economic performance, among all operational modes. Therefore, to address the optimal long-term construction/expansion planning of the desalination-based water supply system driven by hybrid energy sources (Chapter 4), the short-term operational constraints of this mode of operation is taken into account. It is worth mentioning that for the extended long-term planning model, for each year, only hourly data of two seasons of summer and winter is considered; given the relatively close results achieved in Chapter 3 for the two first and the two last seasons of one year.

Chapter 4- Integrating real-time operational constraints in planning of water and energy supply

This chapter has been presented at the oral platform in 28th European Symposium on Computer Aided Process Engineering (ESCAPE 28), and published as a chapter in the book series of Computer-Aided Chemical Engineering.

Reference

Vakilifard N, A. Bahri P, Anda M, Ho G. Integrating real-time operational constraints in planning of water and energy supply. In: Computer aided process engineering. Elsevier; 2018. Vol. 43, p. 313-318.

The formatted published paper is presented in Appendix 2, Section A2.4.

Authors contribution

Contributor	**Statement of contribution**	**Signature**
Negar Vakilifard*	All the literature review, optimisation modelling, simulation, data collecting and analysis, writing the manuscript and revising it based on the received feedbacks	
Parisa A. Bahri	Peer review of the paper, assisting in configuring the paper, giving feedback on the draft and principal supervisor of the project	
Martin Anda	Co-supervisor of the project	
Goen Ho	Peer review of the paper, giving feedback on the draft and co-supervisor of the project	

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Abstract

Given increasing urban population, environmental issues and limited natural resources, long-term planning of water supply systems driven by renewable energies is the only way towards affordable secure and sustainable water and energy future. In this context, daily surplus output from grid-connected rooftop photovoltaics (PVs) is a promising clean energy source to be considered in urban water-related energy mix. In this paper, we address the optimal strategic investment decisions of an urban desalination-based water supply system driven by grid electricity and surplus PVs output, considering real-time operational constraints. The model is formulated as a two-level mixed integer linear programming (MILP) problem. The real-time operational constraints associated with water production, storage and transfer are integrated with yearly planning constraints corresponding to desalination plants, storage tanks and pipeline capacities and locations. The optimal decisions are obtained such that the operation of the water supply system has the most compatibility with available renewable energy. The capabilities of the proposed model are tested through a case-study from north-western corridor of Perth, Western Australia.

Keywords: Desalination, Rooftop photovoltaics, Long-term planning, Optimisation

1. Introduction

Urban areas are responsible for high level of water and energy consumptions as a result of being the centres of population and economic development. Supplying increasing urban water and energy demand given the diminishing natural resources and environmental concerns highlights the importance of an analytical long-term planning to address water security and clean energy.

In land-restricted cities located in arid regions, daily surplus output from residential grid-connected rooftop photovoltaics (PVs) is a clean energy source that can be potentially allocated to energy-intensive water supply technologies. This source of energy is the result of the mismatch between load and PV output during the day and due to its intermittency, is a limiting factor for connection of greater number of these systems to the existing electrical grid. Hence, using it for meeting the water-related electricity demand, not only aligns with the sustainable future water supply but can also enable higher level of PV installations in urban areas.

In our previous study (Vakilifard et al., 2017), we addressed the optimal operation of the urban desalination-based water supply system driven by grid electricity and surplus PV output such that it resulted in the highest compatibility with available renewable energy. In the current study, we extend the mathematical model to a long-term planning of such system and include more detailed modelling of some system components (such as pipeline network) as well as detailed financial analysis of the water supply system. The model is formulated as a two-level mixed integer linear programming (MILP) problem combining yearly constraints of long-term planning of water supply system with real-time (hourly) operational constraints. Three tools of geographical information system (GIS), system advisor model (SAM) and Excel analysis are used to provide some of the main model parameters. Accordingly, while the discounted total cost of the water supply system is minimised, the model gives the optimal strategic investment decisions such as the capacities and locations of desalination plants, storage tanks and pipeline as well as optimal operational scheduling of the system including desalinated water production, storage and transfer, such that it has the most compatibility with available renewable energy. A case study from north-western corridor of Perth, Western Australia is then considered to show the application of the model.

2. Methodology

2.1. Problem statement

1. The temporal aspect of the problem is captured considering a planning horizon of 20 years (begins from 2017), two seasons of summer and winter and 24 time blocks representing hours of a day.
2. Four zones are considered in the case-study area using ArcGIS 10 and Excel tools. The zones boundaries were determined based on our previous study (Vakilifard et al., 2017). In each zone and time period, water demand is supplied by desalination-based water supply system. Considering the annual water demand and population growth rate, we used a simple unit loading method (Walski et al., 2003) to forecast water demand in each zone till the end of 20 years. We assumed the constant water demand during all hours of a day.
3. Total water demand is supplied by a decentralised seawater reverse osmosis (SWRO) water supply system composed of desalination plants, storage tanks and a pipeline network. For a given zone, a desalination plant design capacities are selected from 7 discrete values (from 20,000 to 140,000 m^3/day) considering the plant factor of 0.85. Their potential locations were considered to be next to the ocean. For those zones equipped with a desalination plant, a storage tank can potentially be located in the relative population centre to store extra produced water. The design capacities of storage tanks are chosen from 3 different values (5,000, 10,000 and 20,000 m^3).
4. Desalinated water can be transferred between any two adjacent zones. The maximum water that can be transferred is ascertained based on the capacity of the associated pipeline. In this study, we considered a modular design for pipeline network where the design capacity is standard for a flow of 80,654 m^3/day. Additional capacity can be added to the infrastructure annually, as needed.
5. The capital costs and the average operational and maintenance (O&M) cost for different desalination plants capacities were estimated based on (Watson et al., 2003). The capital cost of storage tanks and average O&M cost of storing per unit of desalinated water were determined according to (T&ES, 2015). The capital cost per unit length of pipeline was estimated based on (Shahabi et al., 2017). The operational cost of transferring water was calculated based on the electricity cost of water pumping. All cost data have been adjusted to 2017 Australian dollars ($).

6. Seasonal residential electricity demand and water-related electricity demand are met by electricity sources consisting of residential rooftop PVs output and grid electricity. The maximum grid electricity that can be transferred to each zone is limited by the maximum capacity of the associated substations. Using SAM tool, the maximum possible PV output for each zone is determined based on Perth's weather file (from the solar resource library of the model) as well as PV installation density in each zone.
7. The grid electricity price follows the time of use (TOU) tariff structure for residential and business sectors. For surplus PV output usage, variable electricity charge is implemented based on the net feed-in tariff (FiT). All electricity price data was taken from Synergy, the electricity retailer of Perth.
8. Discount factors for business and residential sectors are calculated based on the discount rates adopted from (WCWA, 2012) and (AEC, 2017), respectively.

Accordingly, the model gives the optimum solution for the following decision variables:

1. The design capacities of water supply system components as well as their locations on yearly basis

2. Real-time scheduling of desalinated water production, storage and transfer

Such that the most compatibility with available surplus PV output is achieved while the discounted total cost of the water supply system is minimised.

2.2. Mathematical formulation

In line with our previous study (Vakilifard et al., 2017), we formulated the problem as a two-level MILP model. The first level objective function concerns the minimisation of the discounted residential electricity cost during planning horizon (z1). The output of this stage is stored in an auxiliary parameter used in the second level of optimisation to calculate the surplus PV output in each time period that can be assigned to both electricity demand of households not equipped with PV systems as well as water supply system. The objective function at this level is discounted total cost of water supply system (z2) minimised over the planning horizon. The main model constraints are given by Eqs. (1)-(21) as follows:

$$z_1 : Min \sum_{t} DF_t^r . \sum_{s} nd_s . \left[Cfe_t^r + \sum_{i} \sum_{b} Ce_{t,s,b}^r . P_{t,i,s,b}^r \right]$$

$$z_2 : Min \sum_t DF_t^{bi} . \sum_s nd_s . \left[Cfe_t^{bi} + \sum_i \sum_b Cr_t^{bi} . RE_{t,i,s,b}^{w} + Ce_{t,s,b}^{bi} . P_{t,i,s,b}^{w} + COM_t . Q_{t,i,s,b} + Cs_t . V_{t,i,s,b} \right]$$

$$+ \sum_t DF_t^{bi} . \sum_i \left[\sum_c Cap_{t,c}^{DP} . XW_{t,i,c} + \sum_m Cap_{t,m}^{STT} . X_{t,i,m} \right]$$

$$+ \sum_t DF_t^{bi} . \left[\sum_{(i,j) \in \{AL_{i,j} | i=j\}} Cap_t^{PI} . np_{t,i} . L_{i,j} . convf_2 + \sum_{(i,j) \in \{AL_{i,j} | i \neq j\}} Cap_t^{PI} . npIJ_{t,i,j} . L_{i,j} . convf_2 \right]$$

Residential energy balance (with PVs):

$$P_{t,i,s,b}^{r} + RE_{t,i,s,b}^{r} = k_1 . D_{t,i,s,b} \tag{1}$$

Residential energy balance (without PVs):

$$P_{t,i,s,b}^{rn} + RE_{t,i,s,b}^{rn} = (1 - k_1) . D_{t,i,s,b} \tag{2}$$

Water-related energy balance:

$$\begin{aligned} & P_{t,i,s,b}^{w} + RE_{t,i,s,b}^{w} = Q_{t,i,s,b} . De^{DP} + \\ & \sum_{j:(i,j) \in \{PL_{i,j} | i=j\}} WTC_{t,i,s,b} . De_{i,j}^{PI} + \sum_{j:(i,j) \in \{PL_{i,j} | i \neq j\}} WT_{t,i,j,s,b} . De_{i,j}^{PI} \end{aligned} \tag{3}$$

PV share constraints:

$$RE_{t,i,s,b}^{rn} + RE_{t,i,s,b}^{w} \leq Surp_{t,i,s,b} \tag{4}$$

$$RE_{t,i,s,b}^{r} \leq MaxR_{t,i,s,b} \tag{5}$$

Grid share constraint:

$$P_{t,i,s,b}^{r} + P_{t,i,s,b}^{rn} + P_{t,i,s,b}^{w} \leq dur_b . MaxPS_{t,i} \tag{6}$$

Water balance:

$$WQ_{t,i,s,b} + WV_{t,i,s,b} + \sum_{j:(i,j) \in \{AL_{i,j} | i \neq j\}} WT_{t,j,i,s,b} = Dw_{t,i,s,b} \tag{7}$$

Plant capacity:

$$DQ_{t,i} = DQ_{t-1,i} + \sum_c AC_c . XW_{t,i,c} \tag{8}$$

$$\sum_c XW_{t,i,c} \leq 1 \tag{9}$$

Storage capacity:

$$SN_{t,i} = SN_{t-1,i} + \sum_m ST_m . X_{t,i,m} \tag{10}$$

$$\sum_m X_{t,i,m} \le \sum_c XW_{t,i,c} \tag{11}$$

Pipeline capacity within zone:

$$DTW_{t,i} = DTW_{t-1,i}. + MaxTW.np_{t,i} \tag{12}$$

Pipeline capacity between zones:

$$DTWIJ_{t,i,j} = DTWIJ_{t-1,i,j}. + MaxTW.npIJ_{t,i,j} \tag{13}$$

Max. water desalinated:

$$\sum_s nd_s . \sum_b Q_{t,i,s,b} \le PF. \sum_s DQ_{t,i} . nd_s \tag{14}$$

Total and Max. water pushed for storage:

$$WTC_{t,i,s,b} = Q_{t,i,s,b} - WQ_{t,i,s,b} - \sum_{j:(i,j)\in\{AL_{i,j} | i\neq j\}} WT_{t,i,j,s,b} \tag{15}$$

$$WTC_{t,i,s,b} \le convf_1 . DTW_{t,i} . dur_b \tag{16}$$

Total and Max. water stored:

$$V_{t,i,s,b} = V_{t,i,s,b-1} + WTC_{t,i,s,b} - WV_{t,i,s,b} \tag{17}$$

$$V_{t,i,s,b} \le SN_{t,i} \tag{18}$$

Max. water transferred between zones:

$$WT_{t,i,j,s,b} \le convf_1 . DTWIJ_{t,i,j} . dur_b \tag{19}$$

Max. water distributed from the storage tank:

$$WV_{t,i,s,b} \le V_{t,i,s,b-1} \tag{20}$$

Unused surplus energy:

$$Surp_{t,i,s,b} - RE^{rn}_{t,i,s,b} - RE^{w}_{t,i,s,b} \cong 0 \tag{21}$$

3. Results and discussion

The two-level MILP model consists of 117,960 constraints and 97,774 variables (including 1,006 binary variables). The model was run in GAMS 24.3.1 software and solved by CPLEX 12.6.

The optimal result gives the accumulated total cost of $ 3,003,833,149 for investment and operation of the desalination-based water supply system. As shown in Figure 1, the optimal investment solution considers desalination plants in all zones in year one, which will be then expanded once in zone 2 and twice in zone 4 during the planning horizon. Except for zone 1, all other zones are equipped with storage tanks to store extra water produced. In zone 1, the whole water demand is met by desalinated water directly assigned from the desalination plant during the planning horizon.

The optimal operational scheduling (on hourly basis) of the system during summer, for a representative zone 3 and year 2023 is presented in Figure 2(A) and 2(B). As expected, the business TOU tariff is not the only affecting factor on the operational scheduling of the system but the availability of renewable energy also plays a significant role. Accordingly, despite the high electricity rate, the highest level of production and hence the water storage occurs during peak electricity period due to the availability of the surplus PV output that can be assigned to water-related electricity demand. The stored water is then used to satisfy the demand for later hours of the peak electricity pricing period when there is no availability of surplus PV output. This is in agreement with our previous study (Vakilifard et al., 2017) where similar operational behaviour was observed for the hybrid energy scenario, in which both grid electricity and PV output were considered to meet the demand.

For off-peak periods, the production of the desalinated water is limited to the water demand directly assigned from the desalination plant. It is also notable that the amount of water transfer obtained is negligible for all zones during the planning horizon. This is because of the fixed installation density assumed for all zones during the planning horizon as well as the necessity of using all surplus PV output. Consequently, in the optimal solution all zones are equipped with a desalination plant and hence there is no need for water transfer. This limitation will be addressed in the future work.

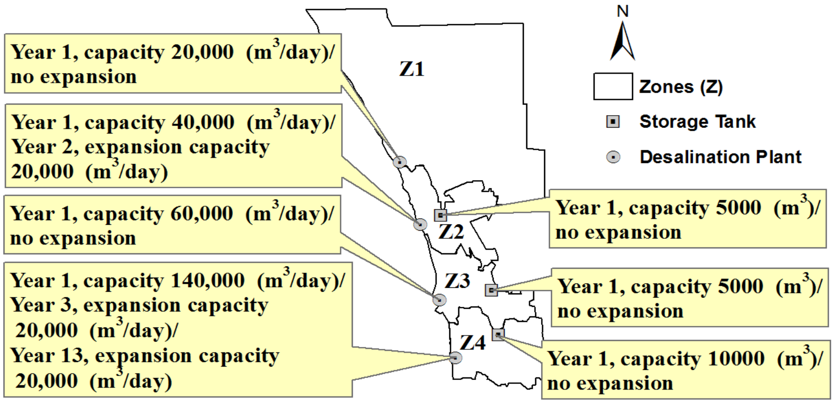

Figure 1: Optimal capacities and locations of desalination plants and storage tanks

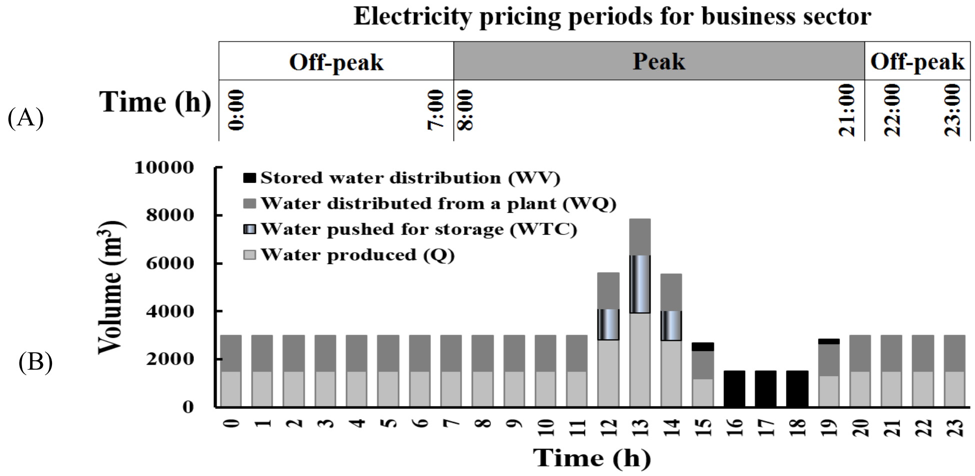

Figure 2: (A) Electricity pricing periods for business sector; (B) Optimal operation of desalination-based water supply system during summer in the representative zone 3 and year 2023

4. Conclusion

In this paper, we addressed long-term planning of a desalination-based water supply system integrated with real-time operational constraints. The model has been formulated as a two-level MILP to give the optimal strategic investment decisions as well as real-time operational scheduling of the water supply system based on availability of the renewable energy and discounted total cost of the system over the planning horizon. The results of applying the model to an urban area located in the north-western corridor of Perth, shows a multi-stage construction and expansion planning as an optimal solution for long term sustainable demand supply.

Nomenclatures

Sets:

AL, PL = allowable zones for water transfer and where pumping is needed, respectively

c= discrete points of plant capacities

i, j = zone

m = discrete points of storage tank capacities

t, s, b = planning horizon, season and time block, respectively

Continuous variables:

DQ = capacity of a plant (m^3/day)

$DTW, DTWIJ$ = capacity of pipeline (m^3/day)

P = share of grid electricity (kWh)

Q = desalinated water produced (m^3)

RE = share of renewable energy (kWh)

SN = capacity of the storage tank (m^3)

V = existing water storage (m^3)

WQ = water distributed from a plant (m^3)

WT = desalinated water transferred (m^3)

WTC = water pushed for storage (m^3)

WV = stored water distribution (m^3)

Parameters:

AC = design capacity of plant with c element (m^3/day)

Cap = capital cost for plant and storage tank ($) and for pipeline ($/km)

Ce = variable grid electricity cost ($/kWh)

Cfe = fixed grid electricity cost ($/day)

COM = plants O&M cost ($/$m^3$)

$convf_1, convf_2$= conversion factors, (day/h) and (km/m), respectively

Parameters (cont'd):

Cr = renewable electricity cost ($/kWh)

Cs = O&M cost of water storage ($/$m^3$)

D = residential energy demand (kWh)

De = water-related electricity demand (kWh/m^3)

DF = discount factor

dur = duration of the time block (h)

Dw = residential water demand (m^3)

k_1 = PV installation density (%)

L = distance (m)

$MaxPS$ = Max. substation capacity (kW)

$MaxR$ = Max. PV output (kWh)

$MaxTW$ = Max. pipeline capacity (m^3/day)

nd = number of days (day)

PF = plant factor

ST = size of storage tank with m element (m^3)

$Surp$ = surplus PV output (kWh)

Integer variables:

$np, npIJ$ = capacity multiplier of pipeline

Binary variables:

X, XW = decisions for storage tank size and plant capacity,
respectively

Superscripts associated with:

bi = business sector (water supplier)

DP = plant

PI = pipeline

r, rn = households with and without PVs, respectively

STT = storage tank

w = water

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Foreword to Chapter 5

In Chapter 4, the developed optimisation model addressed long-term construction /expansion planning of the urban desalination-based water supply system fuelled by hybrid energy sources incorporating the short-term flexible operational constraints. Up to this point, the maximum available surplus PV output was introduced as a parameter to the optimisation models considering a fixed level of PV installation density[1]. Thus, only the effect of available renewable energy on the optimal decisions of the water supply system was explored. The investigation of this effect simultaneous with the effect of optimal water supply system on the potential PV uptake capacity (associated with PV installation density) is the subject of Chapter 5. Accordingly, in this chapter, the optimisation model is extended and solved so that the optimal evolution of potential PV uptake capacity along with the optimal water supply system is achieved in an interactive way.

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[1] Using trial and error, the level of PV installation density was achieved such that results in the complete consumption of PV output after meeting all the electricity demand (as mentioned in Chapters 2, 3, 4).

Chapter 5- An interactive planning model for sustainable urban water and energy supply

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The formatted published paper is presented in Appendix 2, Section A2.5.

Authors contribution

Contributor	Statement of contribution	Signature
Negar Vakilifard*	All the literature review, design of the optimisation framework, all mathematical modelling, simulations, designing of the scenarios, data collecting and analysis, writing the manuscript and revising it based on the received feedbacks	
Parisa A. Bahri	Technical advice on designing the scenarios and sensitivity analysis, giving feedback on the modelling algorithm, reviewing the results and principal supervisor of the project	
Martin Anda	Co-supervisor of the project	
Goen Ho	Peer review of the paper, giving feedback on the draft and co-supervisor of the project	

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Abstract

An interactive multi-period planning model is presented for sustainable urban water and energy supply, taking into account surplus output from grid-connected residential photovoltaics as a part of the water-related energy mix. The two-level mixed integer linear model finds the optimal strategic and operational decisions for a desalination-based water supply system driven by hybrid energy sources and determines the evolution of the potential capacity of a renewable energy technology over the planning horizon. It considers demands, supply systems configuration, resources capacities and electricity tariffs as well as economic, subjectivity and technical criteria for uptaking rooftop photovoltaic systems. The model was then applied to Perth (Australia) and solved for alternative scenarios. The results show operational flexibility and decentralised planning of the integrated system lead to \$251,515,132 less discounted total cost over centralised water supply system operated in fixed mode. They also indicate that decentralised scenario results in 42,765.1 kW higher potential photovoltaics uptake capacity on average in each year over the planning horizon in the case study area compared to centralised scenarios. However, based on the results of the sensitivity analysis, the selection of this scenario as the best alternative highly depends on the parameters values associated with subjectivity criterion and operational and maintenance cost of flexible mode of operation.

Keywords: Photovoltaic system; Grid electricity; Urban water supply; Short-term scheduling; Long-term planning

1. Introduction

Diminishing water and energy resources along with more than ever increasing demand question the security of the future supply especially in cities, the centres of population and economic developments. The situation becomes more critical due to the uncertainties facing policy and decision makers at all levels of urban water and energy supply as well as the lack of coherence between the water and energy sectors.

Water is applied in fuel extraction, transportation, production, refining and processing as well as power generation and power plant cooling. On the other hand, Energy is used in water supply systems from water extraction and pumping to purification and distribution. The latter has an important impact on energy sector when sustainability of urban water supply cannot be ensured but through employing some of energy intensive technologies such as desalination. Construction, operation and expansion of these alternatives impose a significant pressure on energy resources. In fact, in some cases it has been reported that desalination and long-haul transfer are up to twenty three times more energy intensive compared to conventional surface water treatment [1].

Such interactions highlight the necessity of long-term supply planning for each of these commodities in the context of the integrated water and energy management and calls for optimisation modelling frameworks that consider these interlinks for efficient use of existing resources. In this regard, there are several questions that optimisation models need to answer: 1. How are strategic decisions affected by real-time dispatch of water and energy systems? 2- What are the effects of optimal decisions in each sector on the other temporally and spatially? 3- What are the impacts of social and economic uncertainties on the optimal decisions?

To address these challenges, there is a need to capture the water and energy linkage considering the modelling frameworks commonly used in each sector individually and then to compromise and adjust these conventional modelling approaches. In energy sector, there are numerous studies which have focused on optimisation of power generation expansion planning (GEP) problems. Sadeghi et al. [2] provided a detailed overview on GEP problems from different aspects of technological advances, climate change, control strategies and polices as well as applied optimisation models. Guerra et al. [3] developed a mixed integer linear programming (MILP) model for generation and transmission capacity expansion planning of an interconnected power system. Oree et al. [4] reviewed the optimisation techniques in GEP problems with focus on systems integrated with renewable energy sources. With respect to high penetration of renewable energies in GEP problems, Flores-Quiroz et al. [5] and Luz et al. [6] proposed a MILP and multi-objective optimisation model, respectively. In a recent study, Min et al. [7] used a stochastic optimisation approach for long-term capacity expansion of a power system integrated with large-size renewable energy technologies. Other studies have addressed long-term energy mix planning using different optimisation approaches such as stochastic programming [8], MILP model [9] and multi-objective techniques [10].

In water sector, optimisation modelling has been also used for long-term planning of the supply system. Tayfur [11] presented a comprehensive review on the methods used in water resources planning, engineering and management. Adeyemo and Stretch [12] reviewed the application of hybrid evolutionary algorithms in optimising reservoirs. Balekelayi and Tesfamariam [13] provided an overview on techniques employed in water distribution system including rehabilitation. Recently, Marques et al. [14] applied an enhanced simulated annealing algorithm to address a many-objective optimisation design problem in water distribution system in a long-term planning horizon. In another study, Ghelichi et al. [15] proposed a deterministic multi-echelon multi-period model for long-term planning of a municipal water distribution network. They used a two-stage scenario-based stochastic programming to cope with parameters uncertainties such as demand. In regard to desalination-based water supply system, Al-Nory et al. [16] introduced the concept of “desalination supply chain” and presented a methodology to address various aspects which need to be considered in its long-term planning. Using MILP model, Saif and Almansoori [17] and Shahabi et al. [18] presented multi-period construction and capacity expansion planning of a desalination-based water supply system at regional and city scales, respectively.

There are also several studies in the literature focusing on optimal long-term planning of integrated water and energy supply systems simultaneously. Segurado et al. [19] obtained optimal investment and operational decisions for an integrated system consisting of wind-powered desalination plant, reservoir, pumped hydro storage and fossil fuel based generators using H2RES simulation tool and iteration technique. In their next study [20], they focused more on operational strategy and size optimisation based on the parameters values which were foreseen for 2020. They applied simulation along with a derivative free multi-objective optimisation method. From the Pareto optimal set, several solutions could be chosen based on the selected criteria. Using INFINIT (interdependent network flows with induced internal transformation) mode, Ishimatsu et al. [21] conducted a single facility analysis to find the best location of a desalination plant driven by the renewable energy as its primary source. Considering the geographical aspect of the problem, they used a MILP- based model to minimise both total cost and CO_2 emissions to find a solution at national scale (Saudi Arabia) in 2030. Novosel et al. [22] employed the EnergyPlan model to investigate the effect of different but fixed configurations of an integrated desalinated water and energy supply system on the share of renewable energy as well as their benefits on the Jordanian energy supply system in 2020, 2030 and 2050. In another study, Caldera et al. [23] used the linear programming (LP)-based model integrated with levelised cost (LC) analysis to indicate the benefit of providing the total desalinated water demand solely with renewable energy in 2030. These models address one-period optimisation problems to indicate the economic and/or sustainability benefits of the optimal system in one/several target year(s) in the future. They act as if decisions made in the future are decoupled from those in the previous periods. Therefore, they cannot be accurate representatives of real world problems where planning over time is conducted by partitioning time into a number of time blocks. There are only a few studies have considered this aspect.

Khan et al. [24] proposed a partial equilibrium linear model for optimal spatial and temporal synchronization of two streams of water and energy supply systems over their life-cycle. Dubreuil et al. [25] presented the evolution of different water and energy resource mix in supplying the demand at regional scale over the long-term multi-period planning horizon. They introduced the water-modelling module to the TIAM-FR model, a LP-based energy optimisation model. Parkinson et al. [26] presented a system analysis tool using multi-criteria analysis method for simultaneous long-term capacity expansion planning of water and energy technologies at national scale taking into account the Pareto optimal solution. Lv et al. [27] developed an optimisation model for planning of water-energy nexus systems under uncertainty using an interval- fuzzy chance- constraint programming method. Saif and Almansoori [28] addressed simultaneous optimisation of water and energy supply chain problem. They applied a MILP model to optimise long-term capacity expansion and operation of an integrated system consisting of desalination, power and renewable energy power plants. They considered different desalination processes as well as the possibility of water and power transfer among different zones in the studied region.

These optimisation frameworks, however, have been developed at national or regional scales and naturally do not capture the complexities of the integrated system configurations. Therefore, they cannot be directly downscaled for the city scale. Additionally, they have taken into account the static operational constraints, which cannot adequately guarantee the validity and robustness of investment decisions as well as stability of the supply systems equipped with renewable energy technologies. In these cases, operational flexibility is a key factor which needs to be considered in the long-term planning due to its compatibility with inherent intermittency of this source of energy. This factor has been considered in optimisation studies only focusing on the operational aspect of the desalination plants/supply systems integrated with renewable energy sources. For instance, Smaoui and Krichen [29] developed a simulation-based algorithm for optimal energy management of a desalination unit powered by renewable energies. Hickman et al. [30] applied a mixed-integer quadratic constrained program for optimal operation of a system consisting of water, power, and co-production facilities. Al-Nory and Brodsky [31] presented a LP optimisation model for hourly scheduling of a desalination-based water supply system integrated with grid electricity and renewable energy sources. To address the operational flexibility, different time frames such as daily [32] and monthly [33] have been also taken into account.

To the best of our knowledge, there is no optimisation model incorporating short-term (hourly) operational constraints in long-term multi-period planning of the integrated water and energy supply systems at a city scale.

In urban areas located in arid and semi-arid regions, residential rooftop grid-connected photovoltaics (PVs) can potentially contribute to supplying sustainable and clean energy. In fact, the advantages of being space-saving and efficient have turned them into an attractive option which compete with large-scale solar farms [34]. However, the highest possible level of their connection to the existing electrical grid is usually restricted due to the dynamic penetration limit considered for grid stability purposes [19]. The intermittent penetration of surplus PVs output occurs during the day, when the systems generate more electricity but there is a lower residential electricity demand.

There are many studies in energy sector which have addressed this issue. Among different approaches such as integrating several renewable energy sources, control strategies, using back up sources and storage technologies, the latter has attracted considerable attention owing to its ability to ensure grid stability and save excess generated energy for later use. For small applications, batteries have been suggested more than other storage technologies mainly because of their fast response, controllability and geographical independence.

Literature is rich in studies focusing on techno-economic analysis and optimisation of the PV-battery system. Using a battery-PV-simulation model, Linssen et al. [35] conducted a techno-economic analysis and determined the cost-effective configuration in various scenarios of economic and regulatory trends. Tomar and Tiwari [36] employed HOMER software for techno-economic analysis of grid-connected PV system in New Dehli considering feed-in tariff (FiT) and electricity rates. Hoppmann et al. [37] provided a literature review on the economics of batteries coupled with small-scale PV systems and investigated the role of different electricity price scenarios on the profitably of the systems with diverse capacities. Yang et al. [38] comprehensively reviewed the studies addressing the sizing of battery energy system and associated criteria as well as applied methods. Khalilpour and Vassallo [39] presented a review on the existing models for the optimal design of the PV-battery systems. They also developed a multi-period MILP model for their optimal configuration, size and operational decisions. Recently, Huang et al. [40] proposed a mathematical decision-making tool for optimal storage capacity in grid-connected PV systems and determined the relationship between storage capacities and the utilization rates of solar energy for efficient use of this energy source. The optimal power flows among different components of grid-connected PV –battery system have been also addressed previously. Sani Hassan et al. [41] developed a MILP model integrated with DER-CAM (distributed energy resources customer adoption model) software tool to optimally determine the power flows among different components of grid-connected PV–battery system. Grover-Silva et al. [42] addressed sizing and placement of distribution grid-connected battery systems taking into account operational strategies using a power flow distribution grid planning tool.

These studies have emphasised the benefits of using battery systems for removing the restriction of PV connection to the existing electrical grid. However, in practice, their application still highly depends on householders preference; even if the possibility of their usage is increased through rising residential electricity tariff, eliminating FiT or implementing incentive schemes to balance their initial cost [43].

An alternative approach to electricity storage is to introduce a deferrable load to the electrical grid that can assist to exhaust the surplus PV output at the time of its generation. In the context of the integrated water and energy management, this means each component of water supply system from the point of production to the end use is designed and operated compatible with available renewable energy. This approach, therefore, leads to a higher PV installation capacity through exploiting its currently unused output. However, it also contributes to meeting a part of the intensive energy demand of desalination, which currently is a barrier to consider it as a sustainable long-term solution for water supply.

Align with our previous works [44] and [45], this study presents an interactive two-level MILP model for the multi-period long-term planning of a desalination-based water supply system driven by grid electricity and surplus PV output at a city scale. Considering short-term operational constraints, the optimisation model captures the intermittency of renewable energy and creates a hard-link between operation of the water supply system and available renewable energies in real-time (hourly) dispatch. The optimal strategic decisions are achieved based on this operational details. Simultaneously, the effect of the added water-related load to the existing electrical grid on the evolution of PV uptake capacity is quantified taking into account the householders' free will. This study, therefore, sheds a light on long-term implications of considering water and energy linkage in supply systems operation and planning and assists policy makers and engineers in making better informed decisions in both sectors. The proposed optimisation model can be used to quantify the interactive impacts of these distinct disciplines in urban demand supply when both sides of demand and supply are involved in the process of decision-making.

1.1. Contribution

This study addresses the multi-period long-term planning of a desalination-based water supply system driven by grid electricity and surplus PV output in urban areas. The main contributions of our work include: 1- short-term based strategic decisions for urban water and energy supply 2- detailed representation of a full day operating of the system 3- Ability to capture the inherent variability of renewable energy sources on hourly basis and incorporating it in both planning and operational decisions 4- Including the considerations of the spatial configuration of the integrated system (centralised vs. decentralised) in both operational and strategic decisions 5- Quantifying the effect of water and energy linkage on evolution of potential installation capacity of renewable energy technology (PVs) temporally and spatially 6- Exploring the relation between economic performance of the integrated system and social and cost factors.

The remainder of the paper is as follows: Section 2 outlines the details of the proposed model. Section 3 describes the case study and alternative scenarios defined to indicate the capabilities of the model. Sections 4 presents the results of the optimal strategic and operational decisions of the integrated system and their effects on the potential capacity of

PVs uptake as well as the results of the sensitivity analysis. Lastly, the conclusion is presented in Section 5.

2. Methodology

In this study, the multi-period long-term planning of urban water and energy supply was addressed by developing an interactive two-level MILP optimisation model integrated with three tools of system advisor model (SAM), geographic information system (GIS) and Excel (Fig. 1).

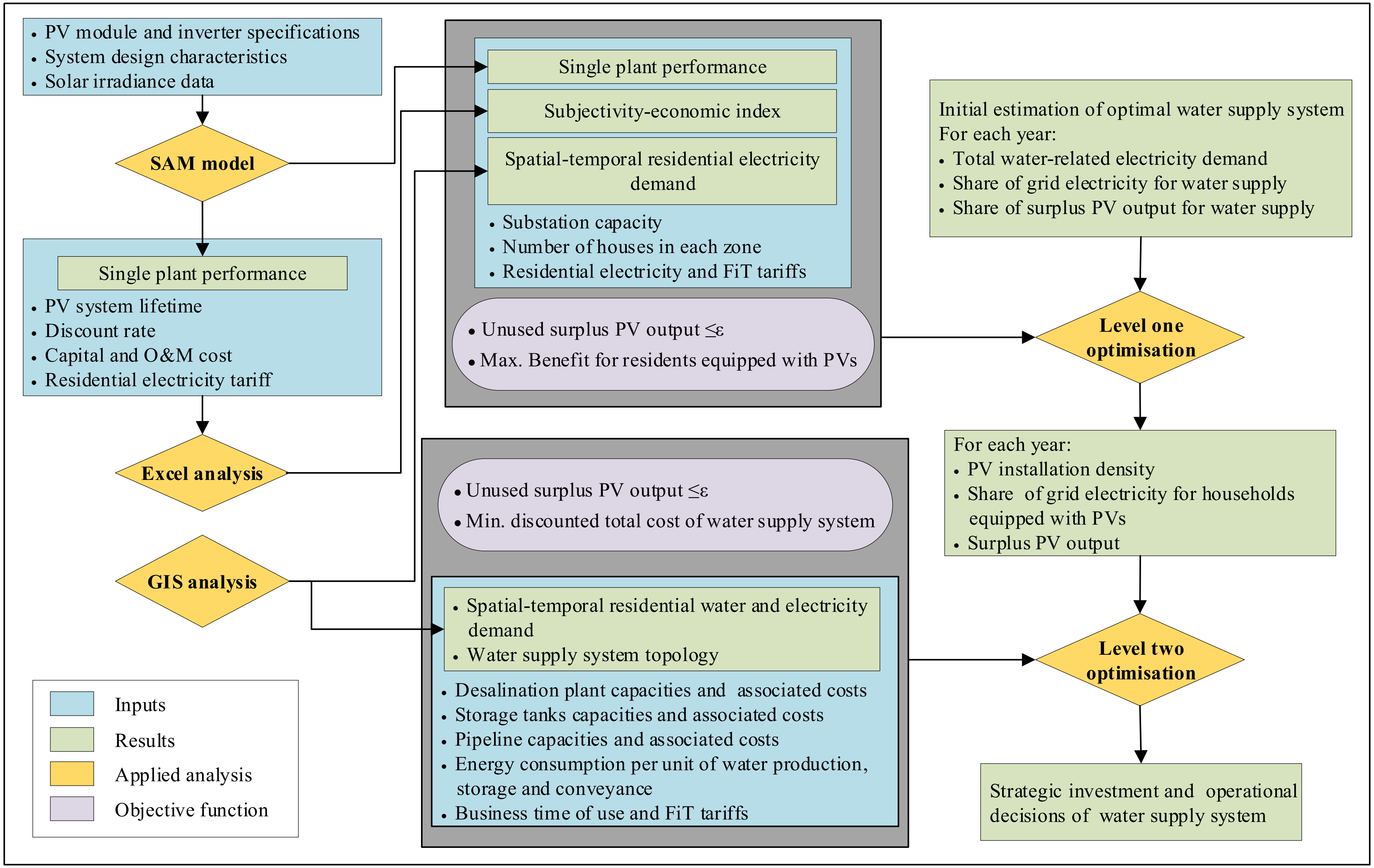

Fig. 1- Proposed optimisation model for urban desalination-based water supply system driven by grid electricity and surplus PVs output

In the first step, the temporal-spatial water and energy demands were forecast over the planning horizon within three time frames of yearly, seasonal (summer and winter) and hourly and for each distinct zone in the case study area. The latter was specified given the population (demand) distribution and service area of zone substations using ArcGIS 10 integrated with Excel analysis.

In the second step, the available resources for meeting the demands were determined. For this purpose, it was assumed that water demand was met by a desalination-based water supply system consisting of desalination plants, storage tanks and a pipeline network with different capacities. In zones equipped with a desalination plant, water demand could be provided from the combination of desalinated water (directly assigned from the plant), stored water and water transfer. In zones not equipped with a desalination plant, demand could be satisfied only via water transfer from allowable (i.e. adjacent) zones. From energy point of view, it was presumed that residential and water-related electricity demands were satisfied by both grid electricity and residential rooftop grid-connected PV systems.

Grid electricity was delivered to the study area through distribution substations, which their maximum capacity was estimated in terms of their transformers' ratings [46]. The potential capacity of renewable energy for each year over the planning horizon was determined through optimisation model based on the generation of a selected PV system size and the number of houses in each zone as well as economic, subjectivity and technical criteria. The performance analysis of a selected PV system size was conducted using SAM model developed by the national renewable energy laboratory [47]. This model is equipped with a solar resource library from which the weather file for different countries and cities can be chosen. Other main SAM model input groups including system components technical specifications as well as system design and configuration are discussed in [48].

In the third step, the data associated with capital and operational and maintenance (O&M) costs of water and energy supply systems as well as electricity tariffs were estimated over the planning horizon. Lastly, the results of the previous steps were introduced to the developed two-level MILP model to achieve the optimal results.

In the following sections, the main aspects of the developed model are presented in more details.

2.1. Two-level mixed integer linear programming model

The optimisation problem was formulated as a MILP due to its flexibility and extensive modelling capability as well as the powerful solvers available commercially. The general mathematical representation of the problem is as follows (adopted from [18]) :

Minimise (or maximise) $$f(x,y) \tag{1}$$

Subject to $$g(x,y) \le b \tag{2}$$

where $$X \in R \ge 0 \tag{3}$$

$$Y \in Z \ge 0 \tag{4}$$

In above equations, $f(x,y)$ expresses the objective function. X and Y are the vectors of continuous and integer (binary) decision variables, respectively. $g(x,y)$ is the vector of inequalities (and equalities) bounded by b, the vector of real constants. R and Z are, in order, the sets of real numbers and integers.

The model consisted of a two-level of optimisation. In the first level, the objective function was to maximise the discounted total benefit that householders could achieve from their PV system in each year over the planning horizon. The economic benefit could be obtained via savings from avoiding grid electricity usage as well as revenues from FiT tariff by selling surplus system output to the grid. The outcomes of the level-one optimisation including the installation density, excess PV output and share of grid electricity in meeting residential electricity demand were then used as parameters in the next level of optimisation. At this stage, the objective function concerned the minimisation of the discounted total cost of construction, expansion and operation of the desalination-based water supply system.

In each level, objective function was subjected to a set of constraints tabulated in Table 1. Section I in the supplementary document, presents the detailed mathematical formulation.

Table 1- Main constraints in each level of MILP model

Optimisation stage	**Constraints**
Level-one optimisation	Electricity balance for households equipped with PVs[1] Electricity balance for households not equipped with PVs[2] Energy resources capacity Maximum potential PV output Surplus PV output
Level-two optimisation	Water balance[3] Desalination plants capacities Storage tanks capacities Water pushed from desalination plant towards storage tank Desalinated water storage Water flows Water-related electricity balance Electricity balance for households not equipped with PVs Energy resources capacity

[1] Electricity demand is supplied by PV system output and grid electricity (Eq. A.2 in the supplementary document.)

[2] Electricity demand is met by surplus PV output and grid electricity (Eq. A.43 in the supplementary document.)

[3] Water demand is satisfied by combination of water directly assigned from the desalination plant, stored in the tank and transferred from other zones. (Eq. A.18 in the supplementary document.)

The model was coded into GAMS 24.3.1 [49], solved by CPLEX 12.6 and reached the final solution in two runs. In each run, both levels of the optimisation were solved in sequence. In the first run, the initial estimation of the optimal water supply system was achieved by allowing the whole area to be equipped with PV systems and relaxing the constraint regarding the unused surplus PV output. Thus, the results were determined without any restriction with regard to available renewable energy. The optimal solution in this run was obtained within a rather large relative optimality gap (< 10%).

The initial estimation for total water-related electricity demand, share of renewable energy and grid electricity in meeting this demand was then applied in the final run to adjust the PV installation density and give the optimal solution under the condition that no unused surplus output is allowed. This constraint led to the most compatible system operation with available renewable energy and contributed to stability of the electrical grid. The relative optimality gap criterion in this run was less than 0.001%.

The above-mentioned strategy for solving the problem was considered due to the interaction between the two levels of optimisation; however, it also assisted in confining the searching region and thus shortened the elapsed time of the program to find the final optimal solution. Below are the main decision variables of the model:

- Construction and expansion capacity and location of different components of the desalination-based water supply system including desalination plants, storage tanks and a pipeline network
- Hourly operational scheduling of water production, storage and transfer in each year
- Share of grid electricity and PV output in supplying water-related energy demand and total energy demand as well as its evolution
- Potential capacity of PVs uptake and its evolution

2.2. Effective criteria on the potential capacity of photovoltaic uptake

The evolution of the potential capacity of the PV uptake was determined through the optimisation process. In this regard, economic, subjectivity and technical criteria affected the value of this variable. The product of the economic and subjectivity indexes were introduced directly to the first level of the optimisation model, as a subjectivity-economic index, to specify the optimal PV installation density. The technical criterion restricted the capacity of installation to ensure the stability of the electrical grid. This criterion was considered as a constraint in both levels of the optimisation (except for the initial estimation of the optimal solution, Section 2.1). Each criterion is described in more details as follows:

Economic criterion: This criterion put the householder's economic priorities into perspective. Using the LC analysis, for each year during the planning horizon it determined whether it is economically worthwhile to uptake the PV system. The methodology used for this purpose was essentially based on [50]. First, the present total cost of a PV system that might be installed in each year during the planning horizon was ascertained by formulating the discounted cash flows of the capital and O&M costs (PC^{cap} and $PC^{O\&M}$) over the system's lifespan (Eqs. (5) and (6)):

$$PC^{cap} = \frac{CPV^{cap}}{(1+rr)^{n_t}} \tag{5}$$

$$PC^{O\&M} = CPV^{O\&M} . \frac{\left[\dfrac{(1+rr)^{PVL}-1}{rr}\right]}{(1+rr)^{n_t+PVL}} \tag{6}$$

where, CPV^{cap} and $CPV^{O\&M}$ (\$) are the capital and O&M costs of a specific size of a PV system, respectively; rr is a discount rate and n_t is the year of the installation (with $n_t = 0$, for the first year within the planning horizon). Finally, PVL (y) is the system lifetime.

The present values of the total cost of a PV system, were then annualised over the planning horizon using the equivalent annual annuity (EAA) method which uniformly distributes the cost of the system [50]. Accordingly, the LC of the PV system for each year that it might be installed was calculated considering the system output and efficiency. The latter was determined based on the annual degradation rate of the system.

In the next stage, the LC was compared to the electricity price tariff in each year. For a given year, should the latter be more than the LC, then it is economically beneficial to install the PV system. The outcome of this analysis was stored in a binary parameter (economic index). An economic index of 1 indicated that the associated criterion was met.

Subjectivity criterion: This criterion accounted for the householder's free will. Once the economic criterion for a given year was fulfilled, the subjectivity criterion specified what ratio of the householders would decide to install PV system[1]. This criterion was defined as a positive parameter (subjectivity index) and could get any value between 0 and 1 assigned directly by the decision maker through interpreting statistics, forecast trends and predicting householders behaviour. The latter could be affected by social awareness or their response to the peripheral components (like electricity markets [51]). The effect of the uncertainty of this parameter on the optimal solutions was specified by completing a sensitivity analysis.

Technical criterion: In this study, the issue of the intermittent surplus PV output was addressed by adding a deferrable load from the operation of the water supply system to the electrical grid. Given that the aim was to investigate the effect of this added load on the potential capacity of the PV uptake, the surplus output was allowed to be fed to the grid, which was not equipped with any storage technologies. Instead, the maximum potential PV uptake capacity was limited to the extent that no unused surplus output remains after meeting all energy demand.

2.3. Cost analysis

In this study, the discounted total cost of the water supply system was minimised to achieve the optimal strategic and operational decisions. Additionally, the total LC (\$/m^3) was also considered as a metric to compare the optimal solutions in different scenarios. LC is an

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[1] In other words, the ratio of rooftops equipped with PVs to their total number

engineering economics index that gives the total unit cost of the product. According to Shahabi et al. [18], it is in fact “the real price at which a long-term contract would need to be negotiated in order for a project to breakeven in net value terms”. Given the project lifetime and discount rate, LC was calculated in terms of the levelised capital cost (LCC (\$/m^3)) and levelised operational cost (LOC (\$/m^3)) as given by Eqs. (7)-(9):

$$LC = LCC + LOC \tag{7}$$

$$LCC = \frac{\sum_{t=0}^{WLT} \frac{CC_t}{(1+r)^t}}{\sum_{t=0}^{WLT} \frac{Q_t}{(1+r)^t}} \tag{8}$$

$$LOC = \frac{\sum_{t=0}^{WLT} \frac{OMC_t}{(1+r)^t}}{\sum_{t=0}^{WLT} \frac{Q_t}{(1+r)^t}} \tag{9}$$

where, CC_t and OMC_t (\$) are, in order, the capital and operational costs of the water supply system occurring in the year t and Q_t is the total water production. r is the weighted average cost of capital (WACC) for water supplier and WLT is the lifetime of the project.

3. Case study and scenarios description

The north-western corridor of Perth, capital of Western Australia, was chosen as a case study to demonstrate the capabilities of the proposed model. This city has a population of more than two million people and due to its reliance on groundwater pumping and desalination, has been the highest energy intensity for water supply among major cities in Australia [52]. Currently, about half of water demand in Perth and surroundings is supplied by two seawater desalination plants (Perth and Southern) [53]. However, owing to urbanisation and the impact of climate change on groundwater resources, it has been suggested that a new 100 GL/y desalination plant, northern seawater desalination plant, needs to be constructed to meet the future demand in northern suburbs [54].

In this study, it was assumed that desalinated water is the only water resource supplying the demand in the case study area. Therefore, the problem was solved for three alternatives of desalination-based water supply system without considering the existing water supply infrastructures. Accordingly, business as usual (BAU) scenario considered a centralised desalination-based water supply system fuelled by grid electricity (as currently common practices). Two other scenarios were centralised and decentralised systems driven by both grid electricity and surplus PV output, named CGPV and DGPV, respectively. Regarding the level of water production in desalination plants, no hourly variations were considered for the fixed mode of operation in BAU and CGPV scenarios. In the DGPV, however, the flexible operational scheduling was taken into account. Further details of different modes of operation can be found in [44].

The data collected for the case study composed of sets with both discrete values (i.e. water supply components capacities and cost data) and continuous values (i.e. distance and pumping elevation among allowable zones). Considering a planning horizon of 15 years, 2 representative days for seasons of summer and winter, 24 hours of a day as well as 4 zones, the temporal datasets of water and energy demand included 2,880 data points. For each zone in the study area, the parameters datasets like maximum capacities of substations, which were defined on yearly basis, included 60 data points. The yearly datasets such as cost data consisted of 15 data points, however, with regard to the grid electricity tariffs they increased to 720 data points considering 24 hours of the representative day in each season. The following sections describe the case study data in more details.

3.1. Water and energy demand and supply systems

Water and residential energy demands in each of the four zones (Fig. 2) within the case study were estimated based on the demand per capita derived from [44] and the annual population growth of around 2.6% adopted from [55]. In this study, daily water demand was assumed to be the same in both seasons while residential energy demand varied. The average annual estimated water and residential energy demands in each zone are tabulated in Tables A.1 and A.2 of the supplementary document, respectively.

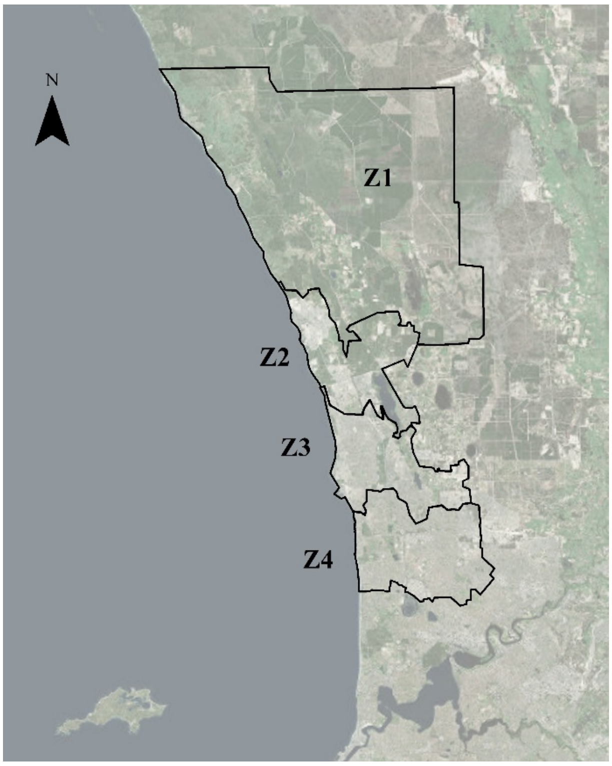


Fig. 2- Case study area and zone (z) boundaries

A seawater reverse osmosis desalination-based water supply system was considered to satisfy the required water. This technology was chosen since it is more likely to stay as the dominant desalination technology over the longer period due to its lower costs and energy consumption as well as ongoing technical advances [56]. The water supply system included desalination plants, storage tanks, and a pipeline network which their capacity/ size(s) could be selected from different values summarised in Table A.3 of the supplementary document. Desalination plants and associated storage tanks were assumed to be located next to the ocean and in the relative centre of population, respectively. The number of days the plant operates divided by the total number of days in the planning horizon is the plant factor, which allows an ample time for preventive maintenance and unforeseen shutdowns. According to [57] it was set 0.85 for all desalination plants. The allowable capacities of the storage tanks were determined so that they could place minimum 2 hours and maximum 3 days of water produced in the associated desalination plants, respectively. Similar to [44] no initial stored water was considered at the beginning of the planning horizon.

For BAU and CGPV scenarios, water could be transferred within zone 1 equipped with a large desalination plant or from this zone to others. This zone was selected for the location of the large capacity plant due to the land constraint in urban areas. In DGPV, water transfer could occur within any zone equipped with a desalination plant or among allowable (adjacent) zones. The details of the distance and pumping elevation differences were based on our previous study [44] (supplementary document, Tables A.4 and A.5). For water production, the average specific energy demand of 4 kWh/m^3 was considered according to [58]. The specific energy demand for water transfer was estimated based on [59].

The energy demand in the case study area was supplied by both grid and PVs (as described in Section 2). The maximum grid electricity that could be delivered to each zone was dictated by substation capacities. The associated specifications of the transformers in each substation were adopted from [60]. Table A.6 in the supplementary document presents the maximum capacity of the substations estimated in each zone over the planning horizon.

The performance of a single 4kW PV system for 8760 hours of a year was simulated using SAM 2016.3.14, since it was the most common system size used in the case study area [61]. SAM model input date was based on our previous study [44] (supplementary document, Table A.7). In this study, the effect of the climate change on PV system performance over the planning horizon was not taken into account.

Considering that the studied area is mainly occupied by single-level houses, the number of existing rooftops in each year was determined according to the estimated population and the number of people in each house based on [62]. In addition, for any given year where the economic criterion for PV system uptake was met, the subjectivity-economic index was assumed to be 1 corresponding to the highest potential capacity of PV uptake. In other words, the whole householders would decide to uptake PV system (subjectivity index = 1) if it was economically beneficial.

3.2. Cost data

All water and energy related costs were converted to 2017 Australian dollars ($) in real terms based on the appropriate exchange rates adopted from [63].

The capital cost of a 4 kW PV system was set 4,230 ($) [64] and assumed to drop at a rate of 1.5% per annum over the planning horizon [65]. The system O&M cost is usually set as a percentage of the capital cost and was assumed to be 1% based on [50]. Considering that the useful lifetime of the inverter is less than PV modules (10-15 years of the inverter lifetime against 20 years (or more) of PV modules lifetime [50]), it needs to be replaced after 10 years since its installation. The associated cost was estimated at 5% of the total installed cost of the system based on [66]. The rate of discounting the cost and savings/revenues of the PV system usage in residential sector was considered 6.64% [67].

The price of grid electricity (for business and residential sectors) and FiT tariff (\$0.07135/kWh) were adopted from [68] and [69], respectively. For grid electricity, the price followed the time of use tariff structure for business sector (water supplier) consisting of fixed and variable electricity supply charge. The fixed electricity charge was set for each day of energy consumption while variable electricity charge was defined in terms of the amount of electricity consumption. No increase in electricity price was assumed over the planning horizon according to [65], which projected the relatively constant electricity retail prices per unit of electricity usage for the period between 2020 and 2037 for the south-west interconnected system (the electricity network in Perth and other regions in the south-west corner of Western Australia). It was explained that the cost of large-scale generation certificates under the large-scale renewable energy target will assist to stabilise the electricity prices in this network [65]. Similarly, the FiT tariff price was assumed to be the same in real terms over the planning horizon as most of the FiT tariffs have been discontinued by the Council of Australian Governments since 2012 and replaced with FiT tariffs with much lower rates. In fact, the savings achieved by avoided grid electricity cost have been the more effective motivator to increase the level of installations [65]. It was assumed that the structure of tariffs for both sectors remains constant over the planning horizon.

The capital and O&M costs of desalination plants were estimated based on [57]. For storage tanks and the pipeline network, the associated costs were taken from [70, 71] and [18], respectively. Considering that the cost of water supply electricity usage varied by the source of energy (grid vs. renewable electricity), this cost component was excluded from O&M cost and calculated directly by the optimisation model. The breakdown of the total costs for water supply components was similar to our previous study [44]. Table A.3 in supplementary document presents the capital and O&M costs of different design capacities of desalination plants and storage tank as well as the unit-installed cost of the pipeline with various diameters. The pumping electricity cost associated with O&M cost of transferring water was calculated separately by the model.

Lastly, in order to calculate the discounted total cost of the water supply system, the real WACC of 5.1% was considered for water supplier adopted from [72].

4. Results and discussion

The two-level optimisation model was solved to the relative optimality criterion of 0.001% using the approach described in Section 2.1. The mathematical formulation was originally developed for DGPV scenario, and for other scenarios, the required constraints were added or modified to address their specific requirements. The statistics of the model for each scenario are summarised in Table 2.

Table 2- The model statistics for each scenario in the final run

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 (%)
BAU	126,551	56,381	56,051	330	5,746	10	-1
CGPV	126,551	59,261	58,931	330	5,076	11	-
DGPV	126,491	106,571	105,791	780	10,161,396	10,090	0.001

[1] The problem was solved to the optimality

The number of variables in BAU and CGPV scenarios was relatively the same and it increased significantly in DGPV scenario. The reason can be explained from two aspects. First, the location of siting the desalination plant in BAU and CGPV scenarios was limited to zone 1 while to find the best possible decisions in DGPV scenario all probable locations for siting water supply components needed to be taken into account. Second, the difficulty of finding the solution in presence of a wide range of time scales (in this case, yearly, seasonal and hourly), did not exist in BAU and CGPV scenarios but in DGPV. This is due to the constraint considered for the fixed operation in centralised scenarios, which limited the feasible searching region and led to the same optimal value for the majority of the operational-related variables on yearly basis. In contrast, in DGPV, the optimal values in each of the introduced time scale needed to be explored due to the flexible operation of the system. Accordingly, the elapsed time of the programme in this scenario was considerably longer (around 1,000 times).

Although the number of variables was much greater in DGPV scenario compared to BAU and CGPV, owing to applying the same structure of the model (i.e. the constraints indices set), the number of generated constraints remained relatively the same in all scenarios.

Lastly, as indicated in the last column of this table, the model was solved to the optimality in BAU and CGPV scenarios and met the selected relative optimality criterion in DGPV implying that CPLEX produces strong bounds for optimal integer solution.

4.1. Optimal strategic decisions

The optimal solution resulted in the discounted total cost of about \$2,495, \$2,413 and \$2,244 million, in BAU, CGPV and DGPV scenarios, respectively.

In both BAU and CGPV, zone 1 was equipped with a centralised desalination plant, which met the whole demand during 15 years planning horizon (Fig. 3a). However, CGPV showed \$82,139,609 less accumulated total O&M cost of the system compared to BAU due to incorporating the renewable energy in its water-related energy mix (Table 3). On the other hand, the optimal solution in DGPV led to a decentralised system configuration consisting of two desalination plants sitting in zones 2 and 4 in the first year and another plant in zone 3 in 2019. In this scenario, the discounted capital cost was \$8,035,261 more than centralised scenarios reflecting the absence of economies of scale of smaller desalination plants. However, its better economic performance can be explained by the discounted total system O&M cost achieved around \$259,550,392 and \$177,410,784 less compared to BAU and CGPV, respectively. The reason is associated with the operational flexibility of the system in this scenario, which resulted in taking the full advantage of the available renewable energy.

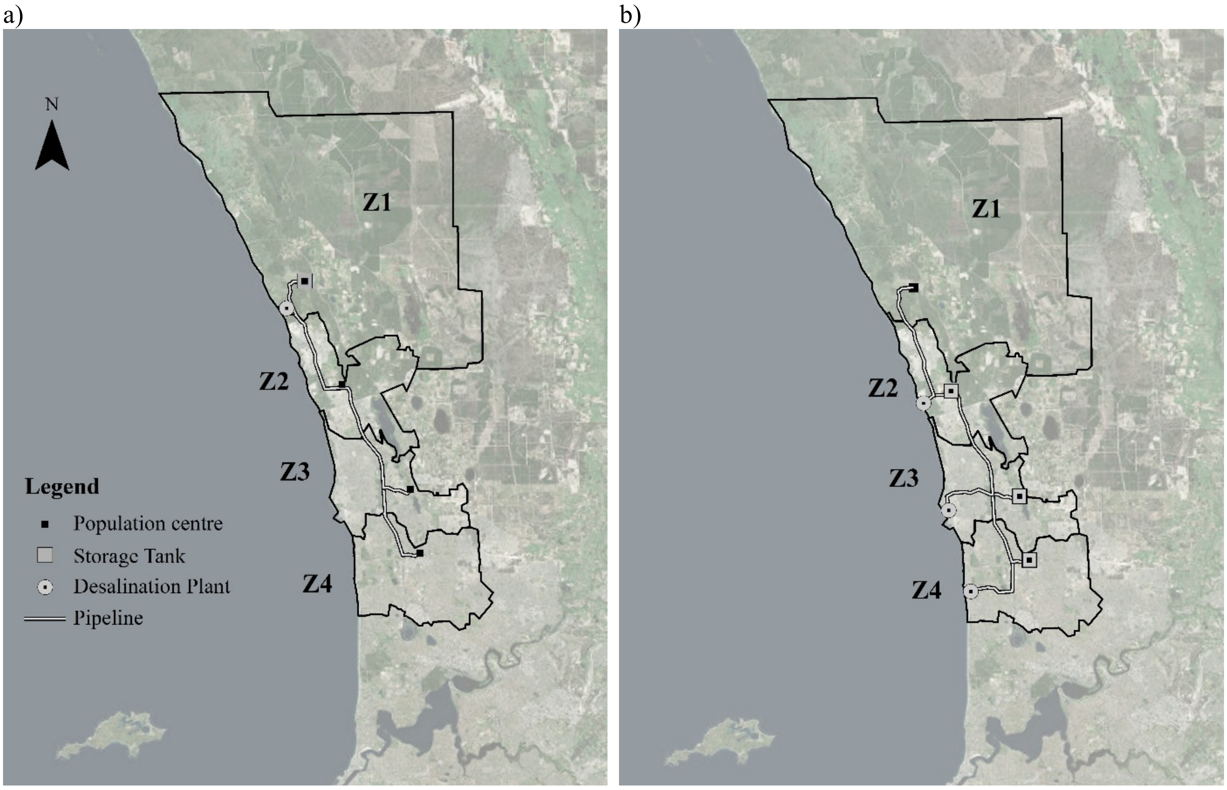


Fig. 3- schematic view of the optimal locations for desalination plants, storage tanks and pipeline network by the end of planning horizon in a) BAU and CGPV and b) DGPV scenarios

Table 3- Results of the optimal water supply system in different scenarios

	Optimal scenarios		
	BAU	**CGPV**	**DGPV**
LC of the water supply[1] ($/m^3) and relative difference with BAU scenario	3.30/-	3.19/3.33%	2.96/10.3%
Absolute difference in discounted total cost of the water supply system with BAU scenario ($)	-	$82,139,609	$251,515,132
Breakdown of the discounted total cost ($)			
Desalination plants and storage tanks (capital)	$1,324,747,281	$1,324,747,281	$1,425,853,173
Pipeline network (capital)	$98,945,428	$98,945,428	$5,874,797
Desalination plants and storage tanks (O&M)	$1,007,580,082	$925,810,190	$808,417,775
Pipeline network (O&M)	$64,102,434	$63,732,717	$3,714,348
Capacity construction and/or expansion details			
Desalination plant location, capacity (m^3/day), construction year, expansion capacity (m^3/day), expansion year	Z1(280,000), year 2017, no expansion	Z1(280,000), year 2017, no expansion	Z2(80,000), year 2017, no expansion Z3(40,000), year 2019, no expansion Z4(120,000), year 2017, (40,000), year 2026
Storage location, capacity (m^3), construction year, expansion capacity (m^3), expansion year	Z1(20,000), year 2017, no expansion	Z1(20,000), year 2017, no expansion	Z2(10,000), year 2017, no expansion Z3(10,000), year 2019, no expansion Z4(10,000), year 2017, (10,000), year 2026
Pipeline (links)	Z1-Z2	Z1-Z2	Z2-Z1
	Z1-Z3	Z1-Z3	Z2-Z3
	Z1-Z4	Z1-Z4	Z4-Z3

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

Overall, the results showed that the operational flexibility overweighs the spatial system configuration when there is the availability of renewable energy. This could challenge the default belief that desalination systems always need to benefit the economies of scale [73] and provide a wider range of integrated system alternatives for the decision maker to address the long-term urban water demand.

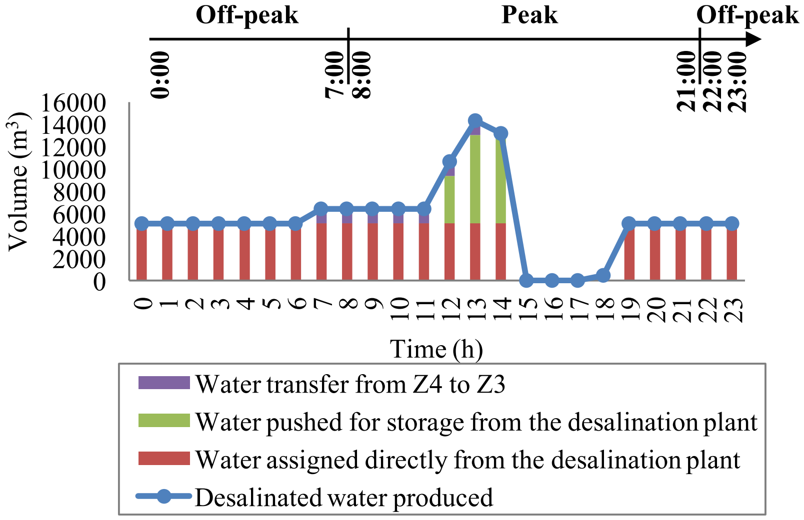
The following section presents the optimal operational details of the water supply system in year 2028 for a representative zone to provide an insight to how short-term operational scheduling can influence the economic performance of the system in long-term horizon.

4.2. Optimal operational scheduling

The optimal operation of the water supply system followed the same logic in all zones and seasons in each scenario. However, there was a slight difference between the paradigm of the operation in summer and winter time. This difference is associated with the variation of available surplus PV output as a result of seasonal fluctuations of solar radiation as well as residential electricity usage profile. In [44], the effect of seasonal changes on the optimal operation of the desalination-based water supply system was discussed in details. In this section, the daily operational details of the system to supply the water demand in zone 4 and year 2028 during summer time is presented. The optimal solution for winter time can be found in Section III of the supplementary document.

In DCPV scenario, water demand in zone 4 was supplied within the same zone. At the point of production, the highest production of water occurred during the availability of surplus PV output, even though it was concurrent with the peak electricity rates period (Fig. 4a). In these hours, the extra water, around 50% of the production, was pushed for storage. At the point of demand, the stored water provided total water demand during the peak electricity rate hours when no renewable energy was available (Fig. 4b). Considering that in this scenario zone 4 was equipped with a desalination plant, the water demand in other times of the day was supplied directly from the desalination plant. This operational scheduling led to the share of 53.53% of available renewable energy in water related energy mix in this zone (Fig. 5) corresponding to \$20,461,995 electricity cost savings for water supply in summer time.

a)



b)

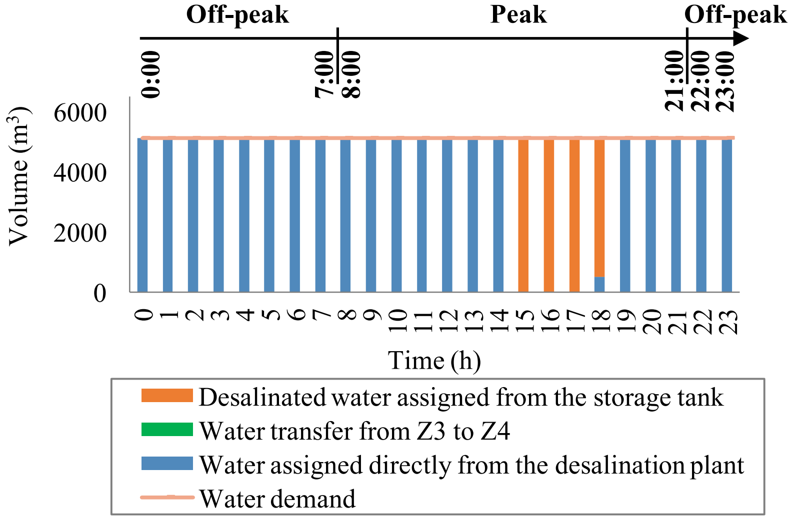


Fig. 4- The operational scheduling of the water supply system in DGPV scenario: a) at the point production b) at the point of demand

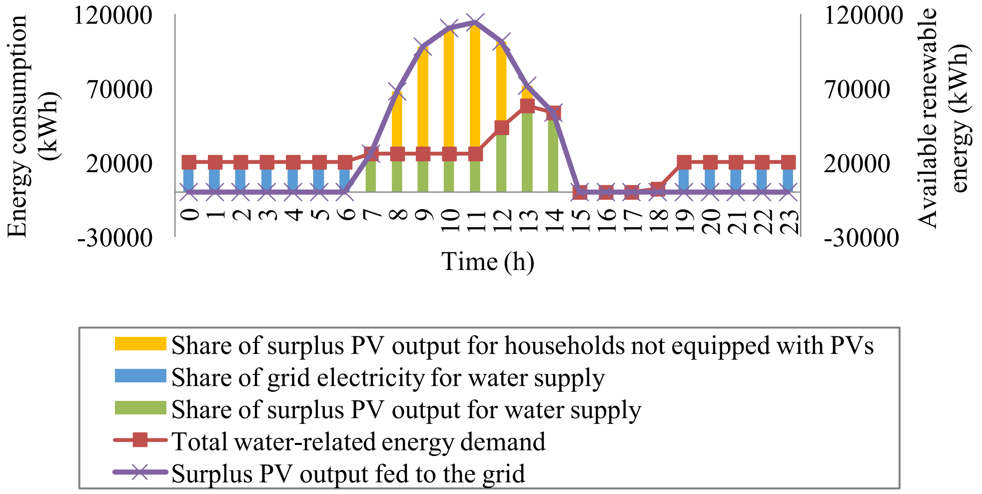


Fig. 5- Share of each energy source in supplying water-related electricity demand at the point of production in DGPV scenario

In CGPV, the point of water production for the whole study area (including zone 4) was located in zone 1 (Fig. 6). Although this resulted in a high water-related energy demand, due to the centralised configuration, the system had access only to surplus PV output in this zone. Thus, while the total available renewable energy was consumed, it only contributed to 10.34% of the total water-related energy demand resulting in $6,800,708 energy savings during summer (Fig. 7a). However, this scenario was still more profitable in long-term run over BAU, which did not include renewable energy in its energy mix (Fig. 7b). It is notable that the different amount of surplus PV output in zone 1 in CGPV and BAU (Fig. 7a and 7b) is related to the maximum PV uptake capacity which has been limited in each scenario to the extent that can be fully consumed by water supply system and households not equipped with PV systems (Section 2.2).

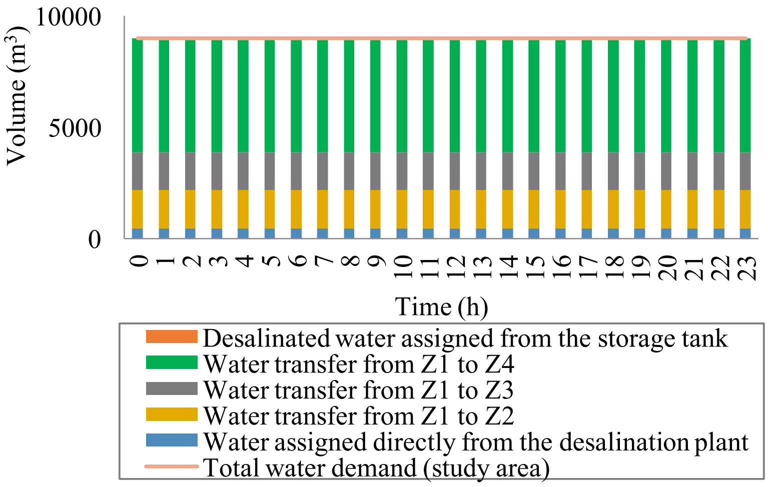
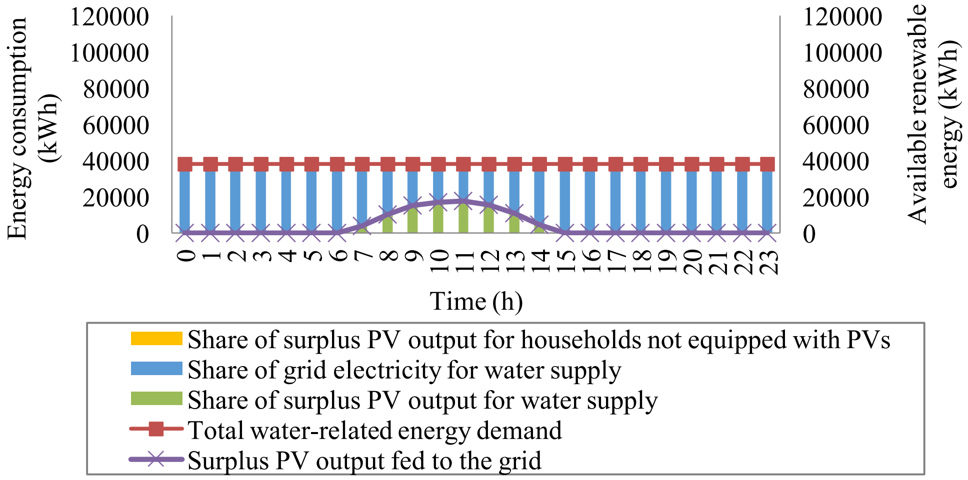


Fig. 6- The operational scheduling of the water supply system in CGPV and BAU scenarios at the point of production

a)



b)

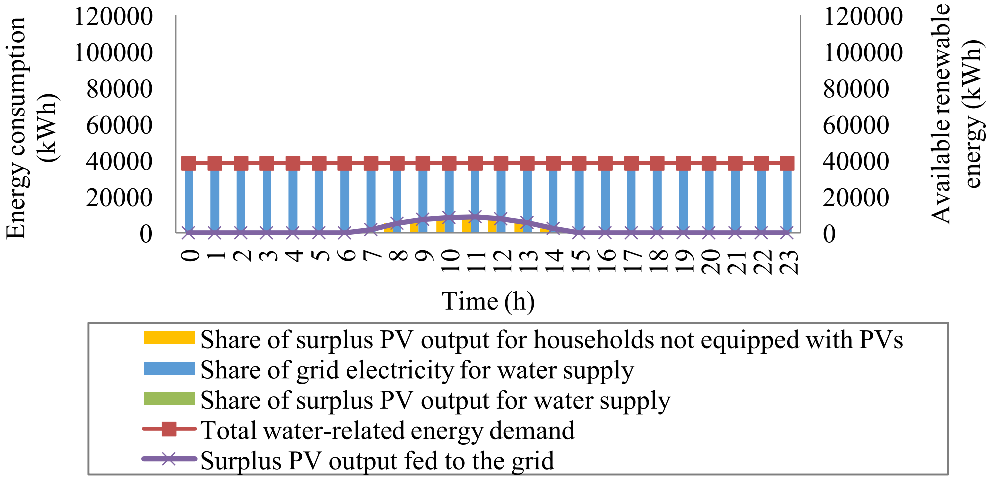


Fig. 7- Share of each energy source in supplying water-related electricity demand at the point of production in: a) CGPV and b) BAU scenarios

At the point of demand (zone 4), in both scenarios the demand was supplied by water transfer from zone 1 (Fig. 8). Therefore, the surplus PV output was not assigned to water supply and exhausted only by households not equipped with PVs (Fig. 9).

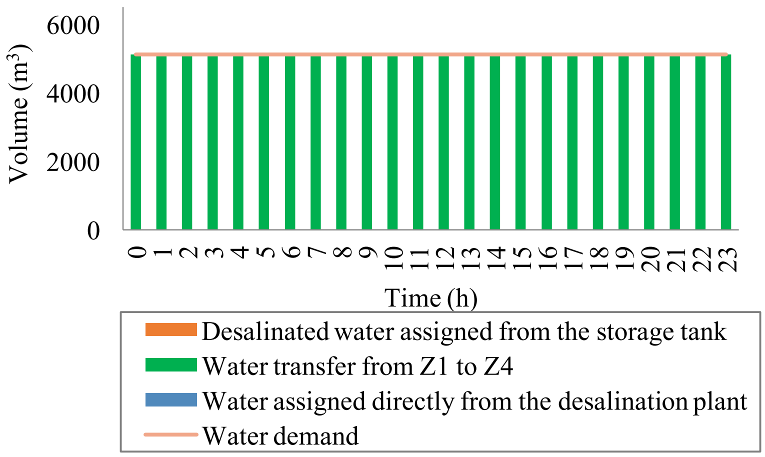


Fig. 8- The operational scheduling of the water supply system in CGPV and BAU scenarios at the point of demand

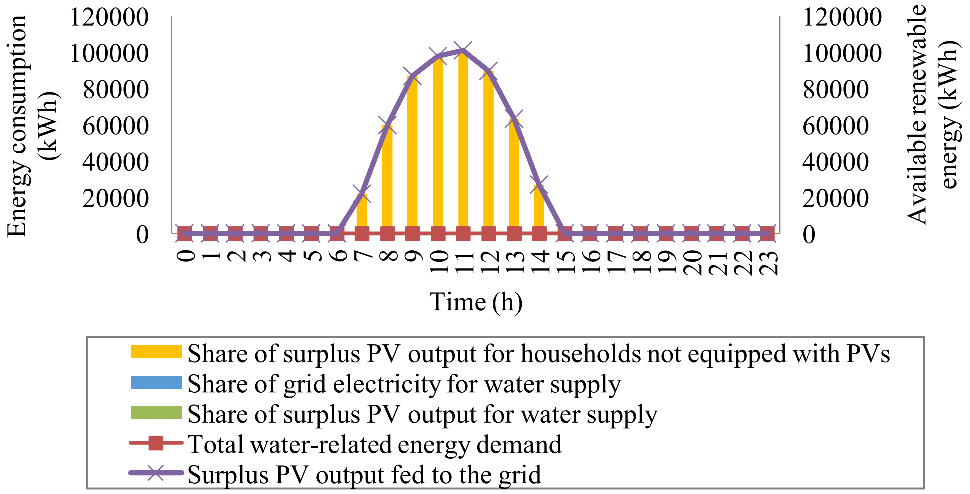


Fig. 9- Share of each energy source in supplying water-related electricity demand in BAU and CGPV scenarios at the point of demand

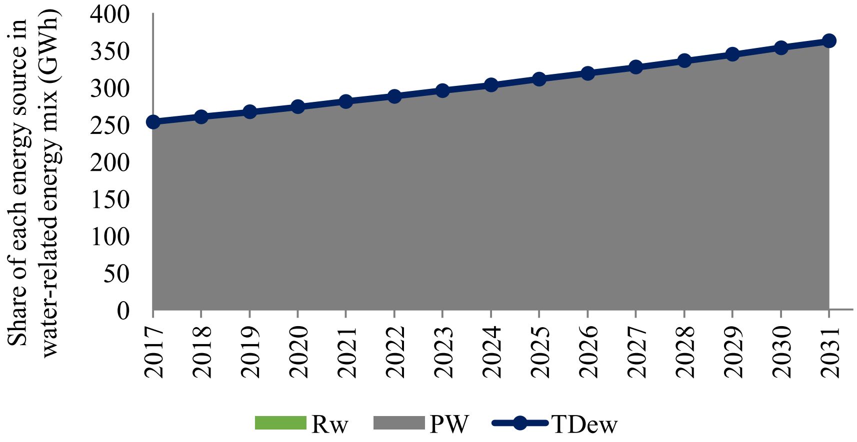
The significant effect of daily operational scheduling and spatial configuration of the system on its short-term economic performance reflects their important role in long-term planning modelling frameworks especially when renewable energy sources are considered as a part of energy mix (similar to GEP problems in energy sector [74]). According to the results, it is evident that disregarding these aspects in planning of the integrated water and energy supply as it has been the case in a few multi-period long-term planning models developed for integrated systems (For instance Ref. [28]) may question the validity and robustness of their investment decisions to be implemented.

4.3. Potential photovoltaic uptake capacity and share of energy sources in water supply

The evolution of renewable energy share in supplying water-related energy demand as well as the potential PV uptake capacity in all scenarios are shown in Figs. 10-12.

As mentioned in Section 3, in BAU scenario, water supply system was operated in fixed mode regardless of available renewable energy. Consequently, total water-related electricity demand was supplied by grid electricity (Fig. 10a) and the potential PV uptake capacity was limited to the extent that the surplus PV output can be fully used at the time of its generation by households not equipped with PV systems. In this scenario, the average total potential PV uptake capacity in zones 1, 2, 3 and 4 was in order, 21,549.3, 83,350.3, 82,760.3 and 248,657.1 kW corresponding to average installation density of 49.9% for all zones in each year over the planning horizon (Fig. 10b).

a)



b)

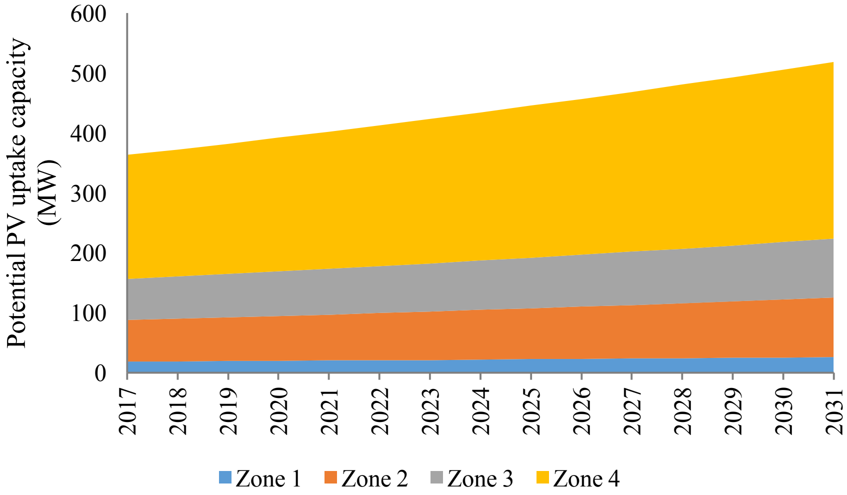
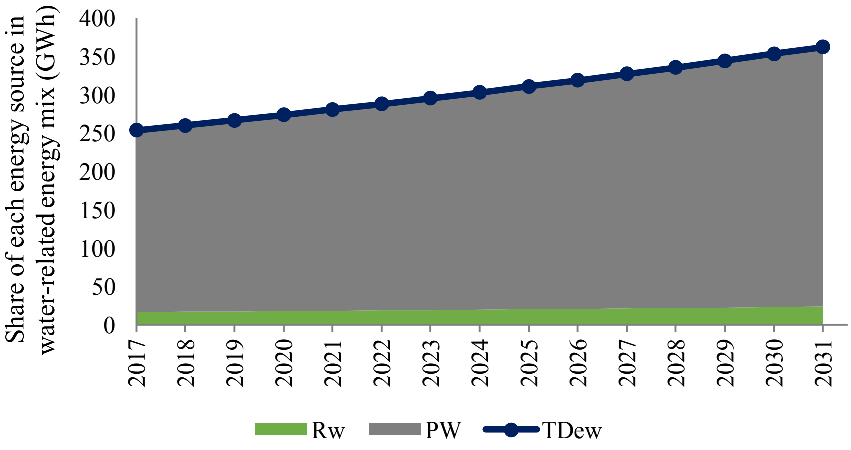


Fig. 10- BAU scenario: a) share of each energy source namely renewable energy (Rw) and grid electricity (Pw) in supplying total water-related energy demand (TDew) over the planning horizon and b) the evolution of potential capacity of PV uptake in the case study area

In CGPV scenario, the available renewable energy in zone 1, where the centralised desalination plant was located, contributed to meeting water-related energy demand. The added load, led to the PV installation density of 100% in this zone and 21,630.8 kW higher potential PV uptake capacity on average in each year over the planning horizon compared to BAU scenario, (Fig. 11b vs. Fig. 10b). Owing to the high water-related energy demand in this zone (associated with supplying the whole water need in the studied area), the total available surplus PV output was consumed by water supply system, although it could only meet 6.4%

of its demand (Fig. 11a). In fact, in this scenario, the share of renewable energy in water supply was restricted by the number of existing rooftops estimated in this zone over the planning horizon. The potential PV uptake capacity and its installation density in other zones (namely, 2, 3 and 4) were similar to BAU scenario (Fig. 11b), bounded by the available residential load of the households not equipped with PVs to exhaust associated surplus output.

a)



b)

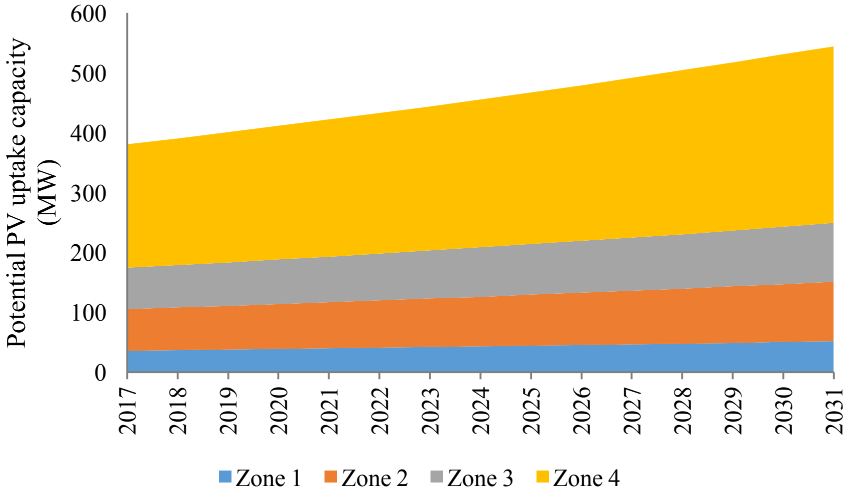
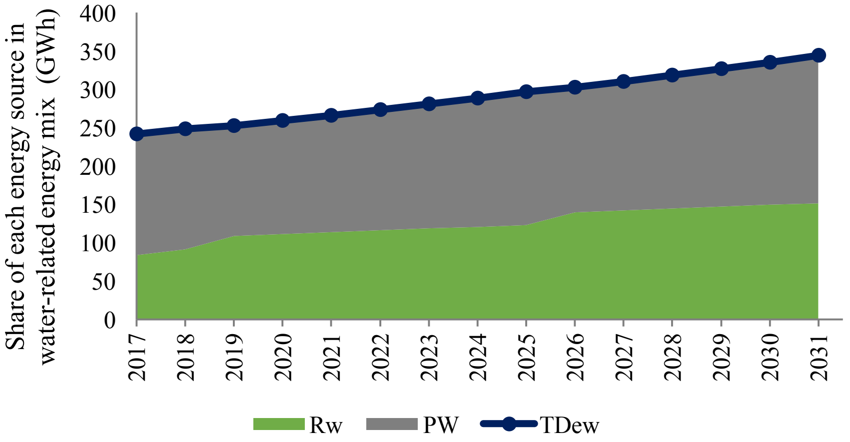


Fig. 11- CGPV scenario: a) share of each energy source namely renewable energy (Rw) and grid electricity (Pw) in supplying total water-related energy demand (TDew) over the planning horizon and b) the evolution of potential capacity of PV uptake in the case study area

In DGPV scenario, around 36% of the water-related energy demand in the case study area was met by renewable energy in the first two years which then increased to 43% in 2019 (Fig.

12a), as a result of the new desalination plant constructed in zone 3 (Section 4.1, Table 3). Over the years between 2019 and 2026, on average 42% of the demand was provided by this source of energy which then raised slightly to 46% (Fig. 12a) due to the expansion of the desalination plant located in zone 4 (Section 4.1, Table 3). In this scenario, the level of the contribution of the renewable energy to water supply was affected by the level of available surplus PV output as well as water demand in each zone, which to some extent dictated the required water-related energy demand. Compared to both BAU and CGPV, the added load from water supply system in zones 2, 3 and 4, in order, led to 11,990.6, 1,729.1 and 29,045.4 kW higher potential PV uptake capacity on average in each year over the planning horizon (Fig. 12b vs. Figs. 10b and 11b). Accordingly, as shown in Fig. 12b, this scenario resulted in the average total potential PV uptake of 21,549.3, 95,340.9, 84,489.4 and 277,702.4 kW corresponding to the average installation density of 49.9%, 57.1%, 51% and 55.7%, in zones 1, 2, 3 and 4 respectively, over the planning horizon.

a)



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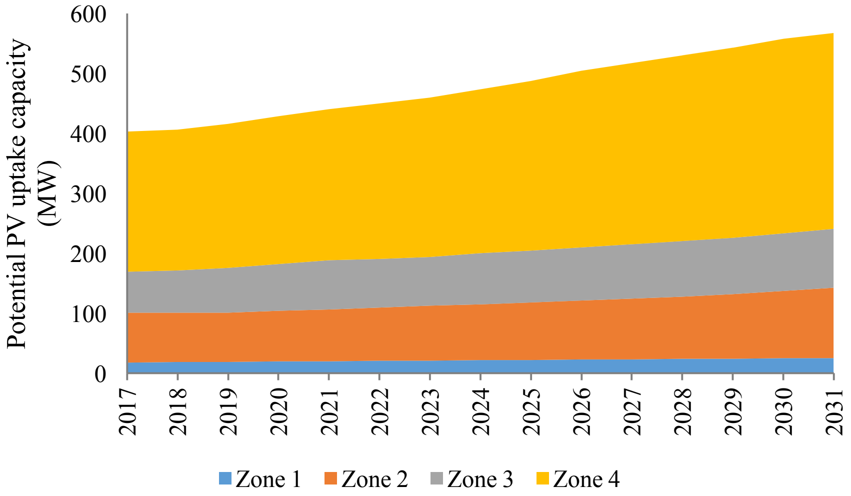

Fig. 12- DGPV scenario: a) share of each energy source namely renewable energy (Rw) and grid electricity (Pw) in supplying total water-related energy demand (TDew) over the planning horizon and b) the evolution of potential capacity of PV uptake in the case study area

In general, adding water-related energy load to the existing electrical grid results in a significant increase in uptake capacity of a small-scale renewable energy technology (rooftop PVs) which best fits the built environment. This results especially applicable in land-restricted urban areas as it assists to explore the potentials and exploit the already existing clean energy sources.

Additionally, the results clearly demonstrate the effect of considering water and energy linkage in the optimal solution in distinct periods over the planning horizon as opposed to the previous studies quantifying this interaction for a single/several years in the future, for instance across their supply systems lifecycles [24] or within technological options [25]. In practice, considering this aspect in long-term planning model can lead to making better informed decisions in each sector as it captures the fluctuations of different parameters (demand, cost, markets, etc.) over time and provides a holistic view of the consequences of decisions made in one sector on the other.

4.4. Sensitivity analysis

In this section, the sensitivity of the optimal strategic and operational decisions towards different values for subjectivity index and the O&M cost ratios of flexible to fixed operational scheduling is shown in Figs. 13a and 13b, respectively.

In respect to potential PV uptake capacity, it was assumed that in case the economic criterion was met, all householders in the studied area would be interested in uptaking PV system (subjectivity index = 1, Section 3.1). Therefore, the only limiting factor was the available load on the electrical grid which could exhaust the surplus electricity at the time of its generation. This assumption, therefore, led to the highest potential PV uptake capacity. However, in practice, despite the economic benefits, some householders might not desire to purchase and install the PV system. To evaluate the sensitivity of the optimal solutions towards different values for subjectivity index, the model was run for four different values, namely 0.75, 0.5, 0.25 and 0. These values represented the ratio of the householders interested in uptaking PVs in case it is economically beneficial (Section 2.2). The subjectivity index of 1 was considered as the reference case.

As expected, the variation in subjectivity index values did not affect the optimal solutions in BAU scenario considering that in this scenario water supply system was operated in fixed mode independent from the level of available renewable energy (Fig. 13a). Similarly, the results indicated high resilience to changes in subjectivity index in CGPV scenario due to the fact that only the renewable energy available in zone 1 contributed to supplying water-related energy demand.

In contrast, the optimal decisions in DGPV scenario showed high sensitivity towards the subjectivity index values. Compared with the reference case, the optimal solutions associated with the subjectivity values of 0.75, 0.50 and 0.25, led to \$11,525,794, \$45,750,176 and \$116,816,743 higher discounted total cost of the water supply system, respectively. In the case of subjectivity index value of 0%, the LC of the system was 19.5% higher compared to the reference case. The discounted total cost of the system in this case was $185,283,888 and $267,423,497 greater than BAU and CGPV scenarios, respectively. This suggests that in the absence of renewable energy, it is not economically beneficial to choose decentralised over centralised water supply system and highlights the importance of developing policies favouring higher installation of PVs (such as incentive programs) in the case study area.

The sensitivity of the optimal decisions in regard to the O&M cost associated with different modes of operation was also investigated. In this study, the solutions in the reference case were achieved regardless of the effect of operational mode of water supply system on this cost component. The reason was due to the fact that the operational mode commonly used in many desalination plants worldwide is fixed and therefore the available O&M cost data are mainly based on this operational scheduling. To investigate the probable adverse effect of the flexible operational mode on water supply infrastructures in terms of maintenance, repair and replacement, the optimal decisions were obtained for four different ratios of O&M cost of flexible operational mode (applied in DGPV scenario) to O&M cost of fixed operational mode (implemented in BAU and CGPV scenarios). The ratio of 1 was considered as the reference case.

Fig. 13b indicates the results of the sensitivity analysis achieved in the ratios of 1.25, 1.5, 1.75 and 2. The results showed high sensitivity towards probable increase in the O&M cost in flexible operational mode. Up to the point where the O&M cost rose to 1.5 times of the fixed operational mode, DGPV scenario had still the economic preference over both BAU and CGPV scenarios. However, when this ratio reached 1.75, the discounted total cost of the water supply system increased to $41,822,339 higher than CGPV scenario and in the case of the ratio of 2, it rose to $76,802,228 greater than BAU scenario. This implies that in order to select the best scenario in real world cases, the possible consequences of flexible mode of operation in terms of extra O&M cost need to be investigated more accurately by long-term running of water supply system components in laboratory and pilot scales.

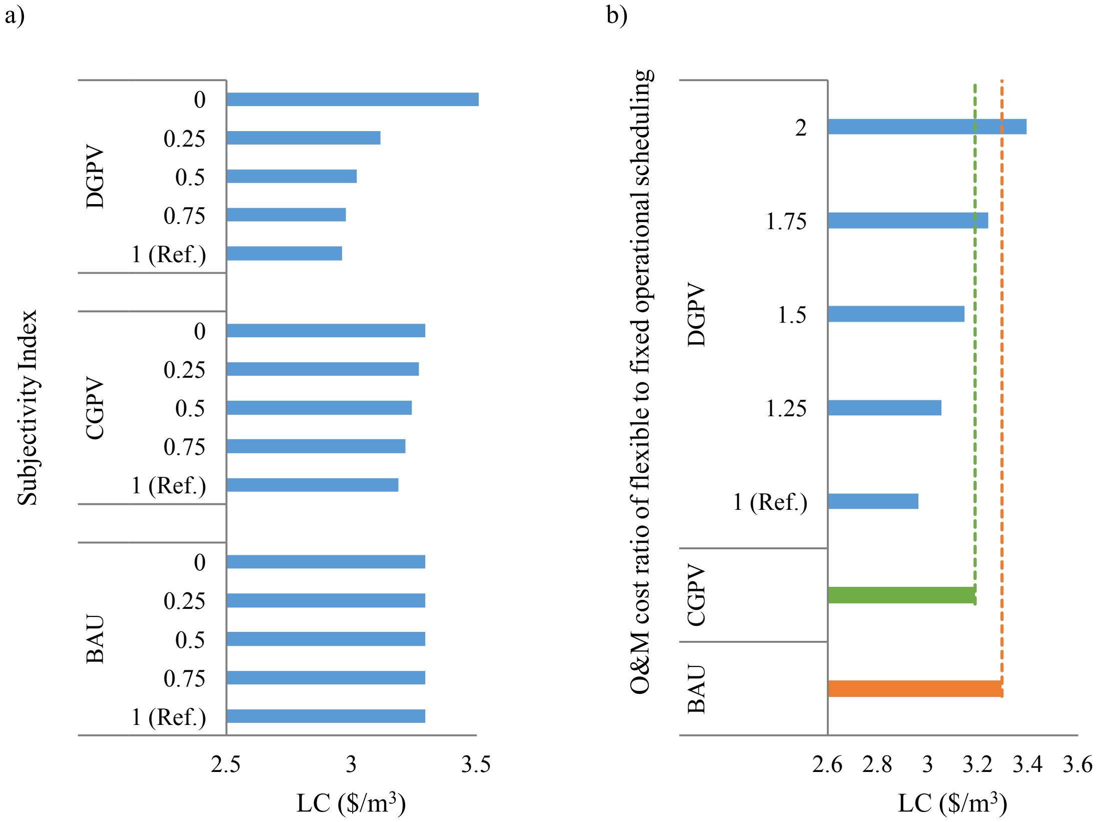

Fig. 13. Sensitivity of the LC of the optimal water supply system in BAU, CGPV and DGPV scenarios for different values of: a) subjectivity index and b) O&M cost ratio of flexible to fixed operational scheduling

5. Conclusion

This paper presented an interactive multi-period long-term planning model for integrated urban water and energy supply system incorporating short-term operational constraints. Grid electricity and surplus output from grid-connected residential rooftop photovoltaics were considered as energy sources for a desalination-based water supply system. Accordingly, the optimal strategic decisions of the system were achieved considering fluctuations of the available renewable energy. The findings of the study include optimal operational scheduling and capacity expansion planning of water supply system as well as the evolution of photovoltaic uptake capacity.

Three key insights were obtained through applying the model to the case study of Perth, Australia. From water sector point of view, it was observed that the operational flexibility and decentralised configuration of the water supply system resulted in 10.3% less levelised cost, accounting for around $251,515,132 discounted total cost saving over the planning horizon, compared to the currently common centralised system. This can question the default belief that desalination systems always need to benefit the economies of scale and provide the decision maker with a wider range of integrated system options to address sustainable water supply when there is the availability of renewable energies.

From energy point of view, it was found that adding flexible water-related energy load to the exiting electrical grid at the time of surplus photovoltaic generation significantly increased the potential uptake capacity of this technology over the long-term planning horizon (on average 42,765.1 kW annually). Therefore, the model is able to capture the linkage of water and energy and is especially useful when it comes to the efficient consumption of already existing sources in urban areas.

Finally, it was evident that the lower level of photovoltaic uptake capacity and higher probable imposed operational and maintenance cost of flexible mode of operation increased the levelised cost of decentralised system up to 19.5% and 14.6%, respectively. This implies the importance of adopting policies favouring higher installation of renewable energy technologies as well as accurate estimation of operational cost component in selecting the best alternative for sustainable supply.

This research considered desalination technology as the only water supply option in the study area. The integrated system, however, can be expanded by incorporating the existing surface water resources as well as the effects of climate change. In this vein, considering the studies dealing with predicting hydrological data [75] or measuring solar radiation [76] can be beneficial. The other research challenge that the future works need to address is to also include more detailed technical constraints associated with the real-time water and energy systems dispatch.

Acknowledgement

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Foreword to Chapter 6

In Chapter 5, the optimal long-term planning and short-term scheduling of the urban desalination-based water supply system, as well as the optimal evolution of potential PV uptake capacity was achieved in an interactive way. The results confirmed that decentralised water supply system fuelled by hybrid energy sources leads to higher potential PV uptake capacity compared to other scenarios over the planning horizon. It also resulted in better economic performance in case the probable imposed O&M cost of the system in flexible mode of operation does not exceed 1.5 times of the fixed operational scheduling. This scenario, therefore, is selected for the next stage (Chapter 6) where indirect GHG emissions costs associated with purchasing grid electricity for water supply is incorporated in the formulation of the objective function (level-two optimisation) in order to investigate its impact on the optimal urban desalination-based water supply system driven by hybrid energy sources.

Chapter 6- The effect of indirect GHG emissions costs on the optimal water and energy supply systems

This chapter is going to be presented as a poster in 29th European Symposium on Computer Aided Process Engineering (ESCAPE 29), and published as a chapter in the book series of Computer-Aided Chemical Engineering.

Reference

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Authors contribution

Contributor	**Statement of contribution**	**Signature**
Negar Vakilifard*	All the literature review, optimisation modelling, simulation, data collecting and analysis, designing of the scenarios, writing the manuscript and revising it based on the received feedbacks	
Parisa A. Bahri	Review of the results and principal supervisor of the project	
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Abstract

This study investigates the effect of indirect greenhouse gas (GHG) emissions on the optimal long-term planning and short-term operational scheduling of a desalination-based water supply system. The system was driven by grid-electricity and surplus output from residential rooftop photovoltaics to deliver water and energy to urban areas. The interactive two-level mixed integer linear programming model took into account demands, system configurations, resources capacities and electricity tariffs as well as GHG emission factor associated with the source of grid electricity. Both system and carbon abatement costs were considered in the formulation of the objective function. The optimal decisions for Perth (Australia) resulted in \$47,449,276 higher discounted total cost but 51,301.3 tCO_2eq less GHG emissions over 15 years planning horizon compared to when only system costs were minimised. Finally, the predominant effect of the indirect GHG emissions costs over system costs on the optimal solutions indicated their high sensitivity towards the source of purchased grid electricity.

Keywords: Grid electricity, Photovoltaics, GHG emissions, Desalination, Optimisation.

1. Introduction

Climate change and increasing water demand in urban areas have made it inevitable to incorporate drought-proof technologies such as desalination in water supply systems. However, meeting their intensive energy demand from fossil-fuel sources leads to higher indirect greenhouse gas (GHG) emissions, which adversely affects the existing water resources and therefore adds further complexities to sustainable supply. Considering renewable energy sources in the energy mix of this water supply option, therefore, could be a potential solution to decrease this effect.

In (Vakilifard et al., 2017), we proposed the idea of employing surplus residential grid-connected photovoltaics (PVs) output in conjunction with grid electricity to drive urban desalination-based water supply system. Using this source of energy not only assists in sustainably meeting the water-related energy demand but also mitigates the barrier of increasing the PVs installation to the existing electrical grid. In (Vakilifard et al., 2018), we developed a mixed integer linear programming (MILP) model to provide optimal strategic decisions of such water supply system incorporating short-term operational scheduling considering PV installation density as a parameter for any given year. In this paper, we extended the model to also investigate the effect of indirect GHG emissions costs associated with purchasing grid electricity on the optimal solutions and to determine to what extent they vary by the source of this energy. Additionally, the interactive effect of added water-related energy demand and installation density (as variable) was addressed through the two-run solving strategy. The results for an urban area located in the north-western corridor of Perth (Australia) were then discussed.

2. Problem statement

The problem was defined in three time frames (yearly, seasonal and hourly) for the planning horizon of 15 years (beginning from 2017). Water and energy needs were determined in 4 distinct zones in the studied area based on the demands per capita, annual population growth and service area of zone substations using ArcGIS 10 integrated with Excel analysis. It was assumed that a decentralised water supply system consisting of desalination plants, storage tanks, and a pipeline network delivers water to the zones. Plants were presumed to be operated in flexible (hourly) mode. The extra water could be desalted when renewable energy was available and could be stored for later use. Plant capacities were selected from 6 discrete values (20,000-120,000 m^3/day) considering the plant factor of 0.85. For storage tanks, the capacities were chosen from 10,000 and 20,000 m^3. Two pipeline capacities associated with the diameters of 30 and 54 in were also taken into account. The potential locations of water supply components in each zone, energy consumption per unit of water produced, stored and distributed as well as the capital and operational and maintenance (O&M) costs were according to (Vakilifard et al., 2018). Grid electricity and PV output supplied residential and water-related electricity demands. The maximum grid electricity that could be delivered to each zone was ascertained based on the associated substations capacities. The maximum capacity of available renewable energy was achieved based on the performance analysis of a 4 kW PV system output conducted in system advisor model (Vakilifard et al., 2017) and the installation density. The latter is the number of households equipped with PV systems in each zone divided by the total number of households and was determined by the model considering the economic-subjectivity index.

This index, in fact, is the product of economic and subjectivity indexes accounting for the economic preference of PV uptake and households' free will, respectively. To determine the economic index, Excel analysis was done based on the methodology described in (Miranda et al., 2015). This binary index is considered to be 1 if it is beneficial to install a PV system. The subjectivity index could be determined by the decision maker and could get any value between 0 and 1. It is the ratio of the households who decide to uptake PV systems (in case it is economically beneficial) to the total households. In this study, it was assumed the economic-subjectivity index is 1 meaning that in case it is economical to install a PV system, all households would decide to be equipped with one. Grid electricity price tariffs as well as the net feed-in tariff were taken from Synergy, the electricity retailer of Perth. The real discount rates for residential and business sectors were adopted from (AEC, 2017; ERA, 2017). The GHG emission factor of 0.7 for purchasing grid electricity from the south west interconnected system (SWIS), the electricity network in Perth, was adopted from (DEE, 2017). It is to be noted that this emission factor is only associated with the environmental impact of the fuels combustion in stationary sources (operational stage). The cost of carbon abatement was considered \$ 40/tCO$_2$eq, taken from (WSAA, 2012). All cost data was converted to 2017 real Australian dollar using appropriate exchange rates from (RBA, 2017).

3. Optimisation strategy

The model was formulated as a two-level MILP model. In the first level of optimisation, the objective function maximised the economic benefits for the households equipped with PV systems (z1). This included savings from avoiding purchasing grid electricity as well as revenues from feeding surplus PV output back into the grid. The outcome of this level of optimisation, namely PV installation density, share of grid electricity in supplying residential energy demand and surplus PV output, were introduced to the level-two optimisation where the optimal decisions for the water supply system were achieved. The objective function at this stage concerned minimisation of the discounted total cost of the water supply system including indirect GHG emissions costs associated with purchasing grid electricity for water supply (z2). The model constraints of the level-one optimisation are presented in Eqs. (1)-(10). The constraints of level-two optimisation were based on our previous study (Vakilifard et al., 2017, 2018).

$$z_1 : Max \sum_{t} DF_t^r . \sum_{s} nd_s . \left[\sum_{i} \sum_{b} Ce_{t,s,b}^r . RE_{t,i,s,b}^r + Cr_t . Surp_{t,i,s,b} \right]$$

$$\begin{aligned} z_2 : Min \sum_{t} DF_t^{bi} . \sum_{s} nd_s . \left[Cfe_t^{bi} + \sum_{i} \sum_{b} Cr_t^{bi} . RE_{t,i,s,b}^w + Ce_{t,s,b}^{bi} . P_{t,i,s,b}^w + COM_t . Q_{t,i,s,b} + Cs_t . V_{t,i,s,b} \right] \\ + \sum_{t} DF_t^{bi} . \sum_{i} \left[\sum_{c} Cap_{t,c}^{DP} . XW_{t,i,c} + \sum_{m} Cap_{t,m}^{STT} . X_{t,i,m} \right] \\ + \sum_{t} DF_t^{bi} . \left[\sum_{(i,j) \in \{AL_{i,j} | i=j\}} Cap_t^{PI} . np_{t,i} . L_{i,j} . convf_2 + \sum_{(i,j) \in \{AL_{i,j} | i \neq j\}} Cap_t^{PI} . npIJ_{t,i,j} . L_{i,j} . convf_2 \right] \\ + \sum_{t} DF_t^{bi} . CTax . f^{GHG} . \sum_{i} \sum_{s} nd_s . \sum_{b} p_{t,i,s,b}^w \end{aligned}$$

Residential energy balance (with PVs):

$$P_{t,i,s,b}^r + RE_{t,i,s,b}^r = k_{t,i} . D_{t,i,s,b} \tag{1}$$

Added share of each energy source:

$$P_{t,i,s,b}^r = P_{t-1,i,s,b}^r + addP_{t,i,s,b}^r \tag{2}$$

$$RE_{t,i,s,b}^r = RE_{t-1,i,s,b}^r + addRE_{t,i,s,b}^r \tag{3}$$

Residential energy balance (without PVs):

$$P_{t,i,s,b}^{rn} + RE_{t,i,s,b}^{rn} = (1 - k_{t,i}) . D_{t,i,s,b} \tag{4}$$

Max. potential PV output:

$$MaxR_{t,i,s,b} = k_{t,i} . dur_b . PV_{s,b} . exisR_{t,i} \tag{5}$$

$$MaxR_{t,i,s,b} = MaxR_{t-1,i,s,b} + addk_{t,i} . kp_t . dur_b . PV_{s,b} . (exisR_{t,i} - exisR_{t-1,i}) \tag{6}$$

Surplus PV output:

$$Surp_{t,i,s,b} = MaxR_{t,i,s,b} - RE^{r}_{t,i,s,b} \tag{7}$$

PV share constraints:

$$RE^{r}_{t,i,s,b} \leq MaxR_{t,i,s,b} \tag{8}$$

Grid share constraint:

$$P^{r}_{t,i,s,b} + P^{rn}_{t,i,s,b} + P^{w}_{t,i,s,b} \leq dur_{b}.MaxPS_{t,i} \tag{9}$$

Unused surplus energy:

$$Surp_{t,i,s,b} - RE^{rn}_{t,i,s,b} - RE^{w}_{t,i,s,b} \cong 0 \tag{10}$$

The optimal solution was achieved in two runs using an interactive approach. In the first run, the initial estimation of the optimal water supply system was obtained regardless of remaining unused surplus PV output (relaxation of Eq. (10)). This led to the maximum PV installation density in the area and the initial estimation of the optimal decisions for water supply system while there was the highest access to the renewable energy. Considering this constraint (Eq. (10)), the initial estimation was then applied in the second run to adjust the installation density and achieve the final optimal solution. Each run included both levels of optimisation.

4. Optimal strategic and operational decisions

The model was coded into GAMS 24.3.1 software and solved by CPLEX 12.6. Two scenarios were considered. In the "minimum system and GHG costs" scenario, the objective function minimised the discounted cost of the system including capital and O&M costs as well as the carbon abatement cost over the planning horizon. This scenario was then compared with "minimum system costs" scenario, which only concerned the minimisation of discounted capital and O&M costs of the system. The optimal results for the minimum system and GHG costs scenario led to \$ 2,291,309,369 discounted total cost, around \$ 47,449,276 higher than minimum system costs scenario. It also resulted in 51,301.3 tCO_2eq less GHG emissions over 15 years of system operation. The optimal results are presented in Figures 1 and 2.

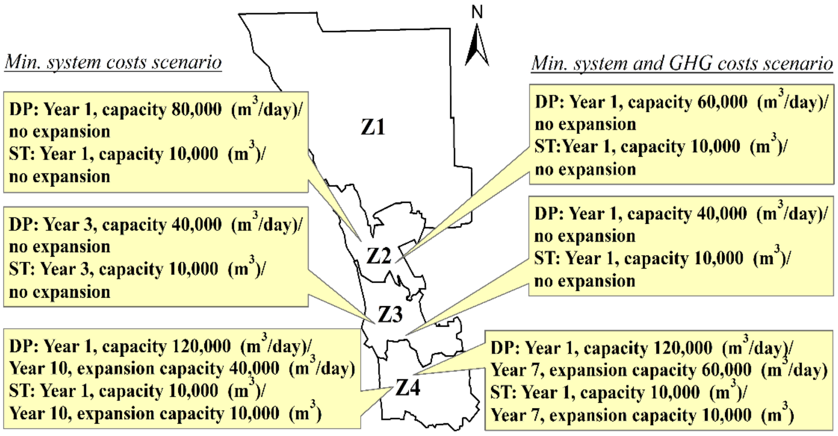

Figure 1: Optimal desalination plants (DP) and storage tanks (ST) capacities located in 4 discrete zones (z) in Min. system costs scenario and Min. system and GHG costs scenario

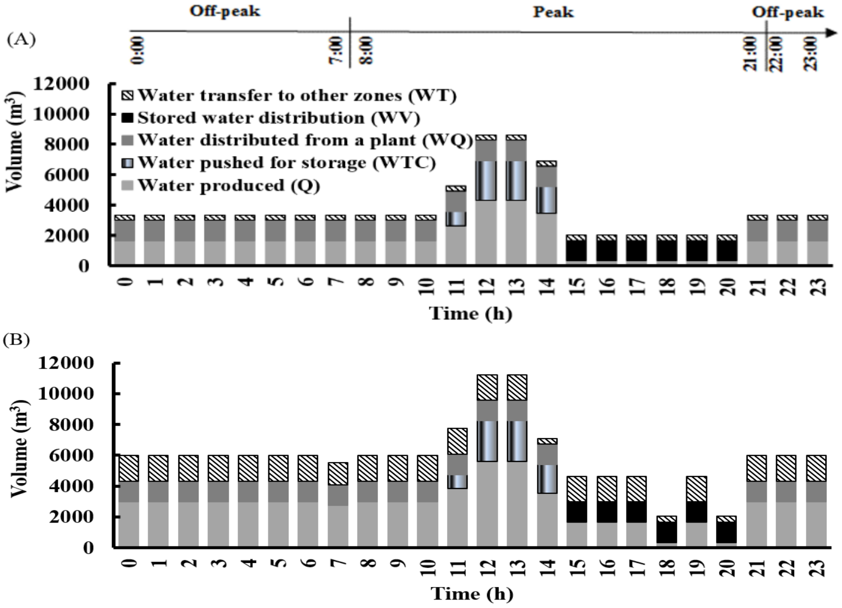

Figure 2: Operational scheduling of the water supply system in the representative zone 2 and year 2018 in: (A) Min. system costs scenario and (B) Min. system and GHG costs scenarios

In both scenarios, three zones of 2, 3 and 4 were equipped with desalination plants (Figure 1); however, in terms of capacities and the timing of construction/expansion of the water supply components, they were different. In minimum system and GHG costs scenario, the model equipped both zones of 2 and 3 with desalination plants and associated storage tanks from the beginning of the planning horizon. Thus, despite the lack of economies of scale of the smaller desalination plants, it located a desalination plant with the capacity of 60,000 m^3/day in zone 2 as opposed to the capacity of 80,000 m^3/day in minimum system costs scenario. Instead, it placed a desalination plant with the capacity of 40,000 m^3/day in zone 3 in year 1 versus year 3 in minimum system costs scenario. The reason is to reduce the energy consumption of water transfer among allowable zones (around 3,640 MWh over 2 years) and decrease indirect GHG emissions costs. It is worth mentioning that although the expansion capacity of the desalination plant in zone 4 in the minimum system and GHG costs scenario was larger than minimum system cost scenario, the earlier time of the expansion neutralised the economic benefits of the larger scale expansion capacity.

Figures 2(A) and 2(B) show the optimal operational scheduling of the water supply system in both scenarios for a representative zone 2 and year 2018. Given flexible mode of operation for water supply system, the paradigm of the daily operational scheduling was achieved relatively the same for both scenarios. Accordingly, the highest water production and storage occurred when renewable energy was available, although it was concurrent with the peak electricity pricing hours. The stored water was then used for providing the water demand in the same zone when it was still during the peak electricity hours but no surplus PV output was available that could be assigned to the water-related electricity demand. The level of water production in zone 2 during peak electricity hours when there was no access to the renewable energy was limited to the demand of its adjacent zones (1 and/or 3). In off-peak electricity hours, the water demand was supplied directly from the desalination plant located in this zone.

5. Sensitivity analysis

Figure 3 depicts the sensitivity of the optimal solution towards purchasing grid electricity from 6 different sources in the minimum system and GHG costs scenario. The associated data was achieved from (Gifford, 2011). The results indicate a relatively high sensitivity towards emission factors higher than 0.148 (municipal waste). In fact, in higher emission factors, the effect of environmental impact was more significant and thus the optimal solution was mainly driven by indirect GHG emissions costs, which led to higher discounted total cost. By decreasing the emission factor, the effect of indirect GHG emissions costs reduced and from a certain point, it did not change the optimal decisions. Thus, the system cost turned to the predominant factor affecting the optimal results. This also explains the relatively same discounted total costs of the system with the minimum system costs scenario in lower emission factors.

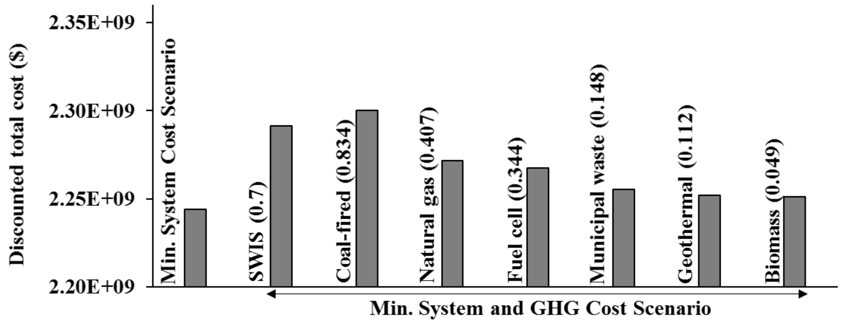

Figure 3: Sensitivity analysis towards purchasing electricity generated from different sources

6. Conclusions

In this study, we proposed an interactive optimisation model for the strategic and operational decisions of an urban water supply system driven by surplus PV output and grid electricity considering both system and carbon abatement costs in the formulation of the objective function. The optimal solutions for an urban area located in the north-western corridor of Perth (Australia) led to less GHG emissions but higher discounted total cost compared to the case where the system costs were the only components of the objective function. Finally, the results of the sensitivity analysis towards purchasing grid electricity from different sources showed the predominant effect of indirect GHG emissions costs over system costs on the optimal solutions in higher emission factors.

Nomenclatures

Sets:
AL= allowable zones for water transfer
c= discrete points of plant capacities
i, j= zone
m= discrete points of storage tank capacities
t,s,b= planning horizon, season and time block, respectively
Continuous variables:
$addP$= added share of grid electricity (kWh)
$addRE$= added share of PV output
$addk$= added PV installation density (%)
k= PV installation density (%)
$MaxR$= Max. PV output (kWh)
P= share of grid electricity (kWh)
Q= desalinated water produced (m3)
RE= share of renewable energy (kWh)
V= existing water storage (m3)
Parameters:
Cap = capital cost for plant (\$) and for pipeline (\$/km)
Ce= variable grid electricity cost (\$/kWh)
Cfe= fixed grid electricity cost (\$/day)
COM= plants O&M cost (\$/m3)
$convf2$= conversion factor (km/m)
Cr= renewable electricity cost (\$/kWh)
Cs= O&M cost of water storage (\$/m3)
D= residential energy demand (kWh)
$CTax$= Carbon abatement cost (\$/kgCO2)
$exisR$= number of existing residential rooftops
f^{GHG}= GHG emission factor (kgCO2/kWh)
DF= discount factor
dur= duration of the time block (h)
kp= economic-subjectivity index
L= distance (m)
$MaxPS$= Max. substation capacity (kW)
nd= number of days (day)
PV= PV system output (kW)
$Surp$= surplus PV output (kWh)
Binary variables:
np, $npIJ$= decisions for construction/ expansion capacity of the pipeline
X,XW= decisions for storage tank size and plant capacity, respectively
Superscripts associated with:
bi= business sector; w= water
DP= plant; PI= pipeline; STT= storage tank
r, rn= households with and without PVs, respectively

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Chapter 7- Conclusions and recommendations for future research

This thesis investigates the optimal decisions for an urban desalination-based water supply system driven by grid electricity and surplus PV output using mathematical modelling integrated with GIS, SAM and Excel tools. The developed model can be applied to any urban area located in arid regions. In this study, the north-western corridor of Perth (WA) was selected as a case-study to complete scenarios and sensitivity analysis at each stage.

1. Conclusions

In this section, a brief description of how the thesis chapters (Chapters 2 to 6) addressed the research objectives (mentioned previously in the section of General introduction) along with the overall conclusion for each chapter is presented.

- **Develop an optimisation model for the operation of an urban desalination-based water supply system driven by hybrid energy sources**

In Chapter 2, a novel two-level LP model was proposed for the optimal operation of the urban desalination-based water supply system driven by grid electricity and surplus PV output (hybrid energy scenario) such that the greatest compatibility with available renewable energy is achieved. The model minimises the grid electricity cost for households equipped with PV systems (level-one optimisation) as well as the system O&M costs (level-two optimisation). It was presumed that the water supply system is operated in flexible mode where water production and storage can vary during a representative day (different time blocks) in two seasons of summer and winter. The optimal solutions were then compared with the case, where grid electricity is the only energy source and can be assigned to the water-related energy demand (base scenario). Using trial and error, the level of PV installation capacity was determined such that no unused surplus PV output remains after meeting the total energy demand. Compared to the base scenario, the optimal results from the hybrid energy scenario showed:

1. 12.1% cost reduction per day for operating the urban desalination-based water supply system
2. 123 % increase in the PV installation capacity in the studied area

Accordingly, the results showed the significance of considering surplus PV output daily fed to the grid for water-related energy mix and highlighted the necessity of a detailed investigation on this mode of system operation versus commonly implemented operational scheduling (semi-flexible and fixed) (Chapter 3).

- **Investigate the effect of different operational approaches on both investment and operation of the desalination-based water supply system driven by hybrid energy sources**

In Chapter 3, the LP model was extended to a two-level MILP model to give both optimal investment and operational decisions for the urban desalination-based water supply system. The model was defined for 24 hours of a representative day in 4 seasons of one year. The specific constraints were considered for three modes of operation (scenarios), namely flexible, semi-flexible and fixed. The electricity cost for households equipped with PV systems and the annualised total cost of water supply system is minimised in the first and second levels of the optimisation model, respectively. In all scenarios, the attempt is to make the most use out of the available surplus PV output. The highest PV installation density was determined via trial and error such that no surplus PV output remains after meeting all the electricity demand. The optimal solutions for three scenarios were achieved and compared. The impact of seasonal change and the sensitivity of the results towards PV installation density and financial rates in each scenario were also investigated. Accordingly, the following results were obtained:

1. For a given year, the flexible scenario resulted in \$9,521,425 (6.2%) and \$18,673,545 (11.4%) better economic performance over the semi-flexible and fixed scenarios, respectively
2. A higher share of available surplus PV output in the water-related electricity mix occurred in the flexible scenario (38%), compared to the semi-flexible (31%) and fixed (29%) scenarios over the planning horizon
3. The flexible, semi-flexible and fixed scenarios, in order, led to 19.9%, 16.3% and 13.7% higher economic benefit in terms of annualised unit cost of water production compared to the existing seawater desalination plant in Perth
4. It was indicated that, in all scenarios, the effect of seasonal changes on the share of different energy sources in providing water-related electricity demand depends on the available solar radiation, the residential electricity usage profile, and the flexibility of the system operation in adjusting to available renewable energy

5. The result of the sensitivity analysis showed a high resilience of the optimal solutions for all scenarios with a variation in the WACC rate in terms of the annualised total cost of the water supply. Instead, they indicated a relatively high sensitivity towards the PV installation density highlighting the importance of implementing policies that facilitate a higher level of PV installations in the studied area.

Overall, it was evident that the flexible scenario is the better choice for operating the desalination-based water supply system when renewable energy is available to be assigned to its energy demand. Accordingly, to explore the optimal long-term construction and expansion planning of such a water supply system, the short-term operational constraints of this scenario were taken into account (Chapters 4, 5 and 6).

- **Develop an optimisation model for long-term planning of the urban desalination-based water supply system driven by hybrid energy sources incorporating short-term operational constraints**

In Chapter 4, the two-level MILP model was utilised for the optimal long-term planning of the desalination-based water supply system driven by hybrid energy sources (based on Chapter 3). The short-term flexible operational constraints were integrated with the long-term planning model. The model minimised the discounted grid electricity cost for the households equipped with PV systems as well as the discounted total costs of water supply system over the long-term planning horizon. For all years of the planning horizon, the PV installation density was considered to be a fixed amount. The following results were achieved accordingly:

1. A multi-stage construction and expansion planning was achieved as an optimal solution for long-term sustainable demand supply
2. The paradigm of the optimal system operation was obtained, similar to the results of the previous chapters (Chapters 2 and 3)

The results of this chapter indicated the capability of the optimisation model to address both strategic and short-term operational decisions of the urban desalination-based water supply system driven by hybrid energy sources. Up to this point, the effect of the determined available renewable energy on the optimal water supply system was explored. Based on the foundation of this study, the model was extended to also include the effect of the added water-related energy demand on the optimal evolution of potential PV uptake capacity over the long-term planning horizon (Chapter 5).

- **Develop an optimisation model to simoultanously address the evolution of potential PV uptake capacity as well as strategic and operational decisions of the urban desalination-based water supply system driven by hybrid energy sources**

In Chapter 5, the optimal solution for the evolution of the potential PV uptake capacity (associated with PV installation density) as well as long-term planning and short-term operation of the urban desalination-based water supply system was achieved in an interactive way in order to complete the water-energy nexus analysis. On the foundation of the previous study (Chapter 4), the two-level MILP model was developed to maximise the benefits of up taking PV systems for residential sector (level-one optimisation) and to minimise the discounted total costs of water supply system over the planning horizon (level-two optimisation). Three economic, subjectivity and technical criteria were incorporated into the model to determine the potential PV uptake capacity in each year over the planning horizon.

The final optimal solutions were achieved in two runs. In the first run, the initial estimation for the optimal decisions of the water supply system was obtained by allowing the whole area to be equipped with PV systems (in case the economic criterion was met) and relaxing the constraint regarding the unused surplus PV output (technical criterion). Thus, the initial estimation for the optimal solutions was determined considering the most accessibility to the renewable energy. This initial estimation was then applied in the second run to adjust the PV installation density and achieve the final optimal decisions for the water supply system considering the constraint associated with the unused surplus PV output.

The results for three scenarios of centralised desalination-based water supply system driven by grid electricity (BAU) and centralised (CGPV) and decentralised (DGPV) desalination-based water supply system driven by hybrid energy sources were obtained and compared. The following results were attained:

1. Over the planning horizon, CGPV and DGPV scenarios resulted in \$82,139,609 (3.3%) and \$251,515,132 (10.1%) less discounted total cost of the water supply system over BAU scenario, respectively
2. Compared to BAU scenario, DGPV scenario led to 42,765.1 kW (~9.8%), on average, higher potential PV uptake capacity in the case-study area in each year over the planning horizon
3. The paradigm of optimal operation of the system in different scenarios was obtained in agreement with the results of the previously developed models (Chapter 2-4)

4. The optimal results showed high sensitivity with the variation of the subjectivity index values in DGPV scenario such that in the absence of renewable energy there is no economic justification to select this scenario over centralised scenarios
5. The optimal results in DGPV scenario also indicated high sensitivity towards the change of probable imposed O&M cost ratio of operating the system in flexible mode over fixed mode such that in the values of 1.75 and 2 there is no economic preference of choosing this scenario, over CGPV and BAU scenarios, respectively

Overall, it was evident that DGPV scenario leads to more cost savings and higher potential PV uptake capacities in the studied area. However, when it comes to applying this scenario in practice, the risks associated with uncertainties of the householders' free will for installing PV system as well as the probable imposed costs associated with flexible mode of operation needs to be taken into account. Despite this, assuming a positive response of householders to the policy and for the purpose of research, DGPV scenario was selected for the next stage where the effect of considering indirect GHG emissions costs in the formulation of the objective function, on the optimal solutions was studied (Chapter 6).

- **Investigate the effect of greenhouse gas (GHG) emissions associated with purchasing grid electricity for water supply on the optimal strategic and operational decisions of the urban desalination-based water supply system driven by hybrid energy sources over the long planning horizon**

In Chapter 6, the two-level MILP model (Chapter 5) was extended to also include indirect GHG emissions costs associated with purchasing grid electricity for water supply, in the formulation of the level-two objective function (minimum system and GHG costs scenario). The results were compared with minimum system costs scenario (similar to DGPV scenario in Chapter 5). The following results were achieved:

1. The minimum system and GHG costs scenario led to \$2,291,309,369 discounted total cost, around \$47,449,276 (~2.1%) higher than that in minimum system costs scenario over the planning horizon
2. The minimum system and GHG costs scenario resulted in 51,301.3 (tCO_2eq) (~2.9%) less GHG emissions over the planning horizon, compared to minimum system costs scenario
3. Considering the flexible mode of operation for the water supply system, the pattern of the daily operational scheduling were achieved, similar in both scenarios

4. The results of the sensitivity analysis towards purchasing grid electricity from different sources showed the predominant effect of indirect GHG emissions costs over system costs on the optimal solutions in higher emission factors

Hence, while the minimum system and GHG costs scenario leads to significantly less GHG emissions over the planning horizon, in practice, adaptation of this scenario highly depends on the implementing policies as well as priorities of the decision maker to determine if it is worthwhile to accept the imposed costs of the less GHG emission water supply system. More investigation on this subject can be a new direction of future research.

2. Recommendations for future research

In this research, the issues of sustainable future urban water supply, as well as the intermittency of surplus residential rooftop PVs output were addressed in the context of integrated water and energy management. Using the proposed model, different aspects of the integrated supply system were investigated and its economic, technical and environmental advantages were explored; However, the latter needs to be evaluated in the context of several limitations. The following describes these points along with the associated recommendations for future research:

- In this study, one PV system size (4 kW) was taken into account to determine the available surplus PV output. However, it is possible to extend the model so that it can consider different PV system sizes. This way it will be possible to decrease the level of uncertainties regarding the subjectivity index by defining different household income levels for residential sector and determining the probable preference of each category for purchasing a specific PV system size. In this regard, the work conducted in [1] can be incorporated into the optimisation model developed in Chapters 5 and 6.

  Moreover, the results of this study can be compared with cases where large-size community-based PV systems are applied to supply water demand (with/without considering surplus residential PV systems).

- In this research, only the effect of the indirect GHG emissions associated with purchasing grid electricity for water supply was taken into account. This investigation can go further to also include direct GHG emissions from desalination-based water supply system from the point of production to end use. In this respect, LCA tools can be integrated with the optimisation model to explore the optimal decisions for the water supply system driven by hybrid energy sources considering its total lifecycle GHG emissions.

- In this work, it was assumed that there is 100% possible land availability for accommodating different water supply components over the planning horizon. However, land decisions might lead to release only a percentage of areas for sitting the infrastructures. This may affect the maximum allowable water supply components capacities which can be selected for each zone and therefore, leads to different optimal solutions. This parameter uncertainty can be investigated for the model proposed in this research through a sensitivity analysis according to [2].

- In this study, water supply system components were considered as deferrable loads to the electrical grid in order to exhaust the intermittent surplus PV output at the time of its generation. Therefore, we allowed surplus PV output to be fed to the electrical grid which had not been equipped with any storage technologies. However, depending on the electricity price in both retail and wholesome markets, the combination of PV-batteries at residential scale could be profitable in the near future due to adopting the optimal configuration of PV and storage technologies (i.e. in terms of system size) and decrease in investment costs of storage technologies as a result of development efforts on different battery types. In this light the work conducted in [3] can be considered. This situation, therefore, could lead to substantial home energy storage across cities which results in significant reduction in available surplus output. Accordingly, the investigation of the effects of this new phenomenon on the optimal decisions is worthwhile to be included in future studies.

  In the same manner, a comparative analysis on the advantages and disadvantages of the approach adopted in this study (i.e. from the economic, technical and environmental aspects) and the case where only storage technologies are applied to mitigate the issue of surplus PV output intermittency, can be a new research direction following this thesis.

Finally, on the basis of the current study, there are other possible research directions by which the present body of work may be extended:

- In this research, desalination was considered the only water supply option meeting the water demand. However, in many regions, other water supply options consisting of rainwater harvesting, groundwater recharge and abstraction and recycling water also play an important role to supply the demand including drinking and irrigation. Extending the model to include the considerations of integrated water resources management such as resources application, capacities, energy demand, and costs, will widen the applicability of the model for the current situation of many urban areas located in arid and semi-arid regions.

- In this research, the capabilities of the proposed modelling framework as well as the consequences of different operational and policy scenarios were investigated considering the city of Perth as a case-study. However, more insight into different water-energy nexus scenario implications can be achieved by adjusting and applying the developed model to other cities located in arid and semi-arid regions such as Middle East and North Africa where there is an opportunity for integrated management of these commodities [4].

- In this research, the uncertainties of different model parameters were investigated depending on the objective of each stage. However, the model can be expanded to also explore the effect of other important uncertainties associated with land use change and deployment of the small-scale energy storage on both feasibility and operational and investment decisions of such integrated system.

  Moreover, it is plausible to obtain the solutions through optimisation under uncertainty (i.e. by using stochastic programming) instead of the sensitivity analysis applied in the current study. This is also one the knowledge gaps in existing optimisation studies in water supply side of the nexus described in Chapter 1 (Section 5) and therefore can open a good direction for future research.

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Appendix 1

In this section, the supplementary document associated with Chapter 3 and Chapter 5 are presented.

A1.1. Supporting document for Chapter 3

1. Specific model constraints for semi-flexible scenario

1.1. Additional constraint for desalinated water production

In semi-flexible scenario, it is assumed that in each zone and season, the amount of desalinated water produced during all hours of a day is constant ($Q_{t,i,s}$ (m^3/day)) and equals to the operational capacity of a desalination plant (($PQ_{c,f}$(m^3/day)) which can be selected from f discrete values (Eq. (A.1)):

$$Q_{t,i,s} = \sum_{c}\sum_{f} PQ_{c,f}.XK_{t,i,s,c,f} \quad \forall t,i,s \tag{A.1}$$

In Eq. (A.1), $XK_{t,i,s,c,f}$ is a binary variable and is activated if the plant operational capacity of $PQ_{c,f}$ occurs in zone i in season s during planning horizon t.

Only if zone i is equipped with a desalination plant with design capacity at capacity breakpoint c, the associated operational capacity can be selected from different operational capacity fraction values. At the same time, at most one operational capacity can be considered for each zone and season during planning horizon t. Eq. (A.2) ensures both constraints as follows:

$$\sum_{f} XK_{t,i,s,c,f} \le XW_{t,i,c} \quad \forall t,i,s,c \tag{A.2}$$

1.2. Modification of constraints common among all scenarios

All equations described in the main manuscript are related to flexible scenario (as mentioned in Section 5 of the main manuscript). In order to apply these equations for semi-flexible scenario, they need to be modified based on the specifications of this operational scenario, as follows:

Eq. (A.3) represents operational and maintenance (O&M) costs of desalination plants, equivalent to Eq. (9) in the main manuscript:

$$OCDQ_{t,i} = \sum_s nd_s . \sum_b C^{eb}_{t,s,b} . P^{wDQ}_{t,i,s,b} + C^{rb}_t . RE^{wDQ}_{t,i,s,b} + \sum_s C^{OM}_t . Q_{t,i,s} . nd_s \qquad \forall t,i \tag{A.3}$$

Eq. (A.4) expresses the upper bound of desalinated water produced, equivalent to Eq. (16) in the main manuscript:

$$\sum_s Q_{t,i,s} . nd_s \leq PF . \sum_s DQ_{t,i} . nd_s \qquad \forall t,i \tag{A.4}$$

Eq. (A.5) determines the amount of desalinated water pushed for storage, equivalent to Eq. (21) in the main manuscript:

$$WTC_{t,i,s,b} = convf_1 . Q_{t,i,s} - WQ_{t,i,s,b} - \sum_{j:(i,j) \in \{L^w_{i,j} | i \neq j\}} WT_{t,i,j,s,b} \qquad \forall t,i,s,b \tag{A.5}$$

Eq. (A.6) gives water-related electricity balance corresponding to water production, equivalent to Eq. (32) in the main manuscript:

$$P^{wDQ}_{t,i,s,b} + RE^{wDQ}_{t,i,s,b} = convf_1 . Q_{t,i,s} . D^{ep} . dur_b \qquad \forall t,i,s,b \tag{A.6}$$

2. Specific model constraints for fixed scenario

2.1. Modification of constraints common among all scenarios

In fixed scenario, for each zone during planning horizon t, the amount of desalinated water produced ($Q_{t,i,s}$ (m^3/day)) remains constant and is equal to the plant design capacity (Eq. (A.7)):

$$Q_{t,i,s} = PF . DQ_{t,i} \qquad \forall t,i,s \tag{A.7}$$

This Equation is equivalent to Eq. (16) in the main manuscript. In addition, the same formulation of Eq. (A.3) and Eqs. (A.5)-(A.6) needs to be applied instead of their equivalents in the main manuscript.

3. Supplementary input data tables

Table A.1- Operational capacity of desalination plants corresponding to each design capacity

Design capacity (m^3/day)	**Operational capacity (m^3/day)**
20,000	8,500/ 17,000
40,000	17,000/ 34,000
60,000	25,500/ 51,000
80,000	17,000/ 34,000/ 51,000/ 68,000
100,000	21,250/ 42,500/ 63,750/ 85,000
120,000	25,500/ 51,000/ 76,500/ 102,000
140,000	29,750/ 59,500/ 89,250/ 119,000

[a] Desalination plants operational capacity are calculated considering the plant factor of 0.85

Table A.2- Breakdown of capital and O&M costs of desalination plants with different design capacities [1, 2]

Total cost breakdown	**Design capacity (m^3/day)**						
	20,000	**40,000**	**60,000**	**80,000**	**100,000**	**120,000**	**140,000**
Capital cost centres							
Direct capital costs	8.05E+07	1.40E+08	2.04E+08	2.74E+08	3.57E+08	3.81E+08	4.43E+08
Freight and insurance	4.03E+06	7.00E+06	1.02E+07	1.37E+07	1.78E+07	1.91E+07	2.22E+07
Interest during construction	2.67E+06	6.96E+06	1.01E+07	1.36E+07	1.77E+07	1.89E+07	2.20E+07
Construction overhead and profit	1.17E+07	2.02E+07	2.90E+07	3.90E+07	5.08E+07	5.43E+07	6.32E+07
Owners direct expense	7.89E+06	1.28E+07	1.78E+07	2.39E+07	3.12E+07	3.33E+07	3.88E+07
Contingency	8.05E+06	1.40E+07	2.04E+07	2.74E+07	3.57E+07	3.81E+07	4.43E+07
Land	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Working capital	5.98E+05	1.10E+06	1.58E+06	2.06E+06	2.56E+06	3.01E+06	3.47E+06
Total capital costs ($)	*1.16E+08*	*2.02E+08*	*2.93E+08*	*3.93E+08*	*5.12E+08*	*5.48E+08*	*6.37E+08*
Annual cost centres							
Labour	2.01E+05	4.02E+05	6.02E+05	8.03E+05	1.00E+06	1.2E+06	1.41E+06
Chemicals	3.79E+05	7.58E+05	1.14E+06	1.52E+06	1.89E+06	2.27E+06	2.65E+06
Energy[a]	-	-	-	-	-	-	-
Repairs and spares	4.17E+05	8.34E+05	1.25E+06	1.67E+06	2.08E+06	2.50E+06	2.92E+06
Insurance	5.78E+05	1.01E+06	1.46E+06	1.97E+06	2.56E+06	2.74E+06	3.19E+06
Concentrate waste stream disposal	1.90E+05	3.80E+05	5.69E+05	7.59E+05	9.49E+05	1.14E+06	1.33E+06
Pre-treatment backwash	7.59E+04	1.52E+05	2.28E+05	3.04E+05	3.80E+05	4.56E+05	5.31E+05
Environmental monitoring	9.49E+04	1.90E+05	2.85E+05	3.80E+05	4.75E+05	5.69E+05	6.64E+05
Performance monitoring	7.59E+04	1.52E+05	2.28E+05	3.04E+05	3.80E+05	4.56E+05	5.31E+05
Indirect O&M costs	3.79E+05	7.58E+05	1.14E+06	1.52E+06	1.89E+06	2.27E+06	2.65E+06
Annual membrane replacement cost	3.41E+05	6.82E+05	1.02E+06	1.36E+06	1.70E+06	2.05E+06	2.39E+06
Annual O&M costs ($)	*2.73E+06*	*5.32E+06*	*7.92E+06*	*1.06E+07*	*1.33E+07*	*1.57E+07*	*1.83E+07*
Annual O&M costs per unit of desalinated water produced ($/m^3)	*0.374*	*0.364*	*0.362*	*0.362*	*0.365*	*0.357*	*0.357*

[a] The energy cost is calculated directly by the optimisation model based on the energy consumption per unit of desalinated water produced and the energy source (grid electricity or PV output) assigned to the demand.

Table A.3- Breakdown of capital and O&M costs of storage tanks with different sizes [3, 4]

Total cost breakdown	**Size (m^3)**		
	5,000	**10,000**	**20,000**
Capital cost centres			
Construction cost of storage tank	1.17E+07	2.02E+07	3.47E+07
Construction contingency	4.11E+06	7.06E+06	1.21E+07
Planning, design, CM, administration, permitting and easements	5.55E+06	9.53E+06	1.64E+07
Land Acquisition	N/A	N/A	N/A
Total capital costs ($)	*2.14E+07*	*3.68E+07*	*6.32E+07*
Annual cost centres			
Wash down water	2.87E+03	5.73E+03	1.15E+04
Pumping costs[a]	-	-	-
Labour costs			
- Daily Check (365@0.5hrs/each)	1.24E+04	1.24E+04	1.24E+04
- Weekly Inspections (52@2hrs/each)	7.05E+03	7.05E+03	7.05E+03
- Monthly Inspections (12@8hrs/each)	6.51E+03	6.51E+03	6.51E+03
- Quarterly Cleaning (4@48hrs/each)	1.30E+04	1.30E+04	1.30E+04
Total operational costs ($)	*4.18E+04*	*4.47E+04*	*5.04E+04*
Repairs and spares	2.38E+05	4.09E+05	7.02E+05
Total maintenance costs ($)	*2.38E+05*	*4.09E+05*	*7.02E+05*
Annual O&M costs ($)	*2.80E+05*	*4.53E+05*	*7.53E+05*
Annual O&M costs per unit of water stored ($/m^3$)	*0.153*	*0.124*	*0.103*

[a] Pumping cost is as a part of energy cost associated with transferring desalinated water from desalination plant in each zone to the storage tank within the same zone. It is calculated directly by the optimisation model based on the energy consumption per unit of water transferred and the energy source (grid electricity or PV output) assigned to the demand.

4. Tables of optimal solution for flexible scenario

Table A.4- Optimal solution for water supply operation at the point of production in each zone during summer in flexible scenario, 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)

Zone	**Variable**	**To**	**Time block**																							
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Z1	WQ (m^3)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WTC (m^3)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WT (m^3)	Z2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Q (m^3)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Z2	WQ (m^3)		1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	273	1,265	1,265	1,265	1,265	1,265	1,265	416	0	0	193	1,265	1,265	1,265	1,265	1,265
	WTC (m^3)		0	0	0	0	0	0	0	993	0	87	844	1,158	1,247	930	185	0	0	0	0	0	0	0	0	0
	WT (m^3)	Z1	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327
		Z3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Q (m^3)		1,592	1,592	1,592	1,592	1,592	1,592	1,592	2,585	600	1,680	2,436	2,750	2,840	2,523	1,778	743	327	327	520	1,592	1,592	1,592	1,592	1,592

Table A.4- (cont'd)

Zone	**Variable**	**To**	**Time block**																							
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Z3	WQ (m^3)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WTC (m^3)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WT (m^3)	Z2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Z4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Q (m^3)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Z4	WQ (m^3)		3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	2,994	0	0	2,105	3,775	3,775	3,775	3,775
	WTC (m^3)		0	0	0	0	0	0	0	0	0	0	0	0	216	3363	3363	3057	0	0	0	0	0	0	0	0
	WT (m^3)	Z3	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256
	Q (m^3)		5,031	5,031	5,031	5,031	5,031	5,031	5,031	5,031	5,031	5,031	5,031	5,031	5,248	8,394	8,394	8,088	4,250	1,256	1,256	3,361	5,031	5,031	5,031	5,031

Table A.5- Optimal solution for water supply operation at the point of demand in each zone during summer in flexible scenario, including water assigned directly from desalination plant (WQ), desalinated water transferred from other zones (WT) and desalinated water assigned from storage tank (WV)

Zone	**Variable**	**From**	**Time block**																							
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Z1	WQ (m^3)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WT (m^3)	Z2	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327
	WV (m^3)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Z2	WQ (m^3)		1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	273	1,265	1,265	1,265	1,265	1,265	1,265	416	0	0	193	1,265	1,265	1,265	1,265	1,265
	WT (m^3)	Z1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Z3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WV (m^3)		0	0	0	0	0	0	0	0	993	0	0	0	0	0	0	849	1,265	1,265	1,072	0	0	0	0	0

Table A.5- (cont'd)

Zone	**Variable**	**From**	**Time block**																							
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Z3	WQ (m^3)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WT (m^3)	Z2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Z4	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256	1,256
	WV (m^3)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Z4	WQ (m^3)		3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	2,994	0	0	2,105	3,775	3,775	3,775	3,775
	WT (m^3)	Z3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WV (m^3)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	781	3,775	3,775	1,670	0	0	0	0

Table A.6- Surplus PV output fed to the electrical grid (Surp) in each zone 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 in flexible scenario

Zone	Variable	Time block																							
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Z1	Surp (kWh)[1]	0	0	0	0	0	0	0	0	641	1,759	2,549	2,877	2,971	2,640	1,861	789	0	0	0	0	0	0	0	0
	Re^w (kWh)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	P^w (kWh)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	TD^{ew} (kWh)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Z2	Surp (kWh)	0	0	0	0	0	0	0	0	2,478	6,803	9,860	11,130	11,493	10,211	7,199	3,052	0	0	0	0	0	0	0	0
	Re^w (kWh)	0	0	0	0	0	0	0	0	2,478	6,803	9,860	11,130	11,493	10,211	7,199	3,052	0	0	0	0	0	0	0	0
	P^w (kWh)	6,449	6,449	6,449	6,449	6,449	6,449	6,449	10,463	0	0	0	0	0	0	0	0	1,388	1,388	2,161	6,449	6,449	6,449	6,449	6,449
	TD^{ew} (kWh)	6,449	6,449	6,449	6,449	6,449	6,449	6,449	10,463	2,478	6,803	9,860	11,130	11,493	10,211	7,199	3,052	1,388	1,388	2,161	6,449	6,449	6,449	6,449	6,449

Table A.6- (cont'd)

Zone	**Variable**	**Time block**																							
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Z3	Surp (kWh)	0	0	0	0	0	0	0	0	2,461	6,755	9,791	11,051	11,411	10,138	7,148	3,030	0	0	0	0	0	0	0	0
	Re^w (kWh)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	P^w (kWh)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	TD^{ew} (kWh)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Z4	Surp (kWh)	0	0	0	0	0	0	0	11,571	25,494	39,387	49,092	53,558	55,415	52,334	44,254	32,978	17,243	2,037	0	0	0	0	0	0
	Re^w (kWh)	0	0	0	0	0	0	0	11,571	20,366	20,366	20,366	20,366	21,259	34,241	34,241	32,978	17,243	2,037	0	0	0	0	0	0
	P^w (kWh)	20,366	20,366	20,366	20,366	20,366	20,366	20,366	8,795	0	0	0	0	0	0	0	0	0	3,230	5,267	13,687	20,366	20,366	20,366	20,366
	TD^{ew} (kWh)	20,366	20,366	20,366	20,366	20,366	20,366	20,366	20,366	20,366	20,366	20,366	20,366	21,259	34,241	34,241	32,978	17,243	5,267	5,267	13,687	20,366	20,366	20,366	20,366

[1] In cases where there is no water-related electricity demand or its amount is less than surplus PV output, it is consumed by existing load from households not equipped with PV systems.

5. Tables of optimal solution for semi-flexible scenario

Table A.7- Optimal solution for water supply operation at the point of production in each zone during summer in semi-flexible scenario, including water assigned directly from desalination plant (WQ), water pushed for storage from desalination plant (WTC), desalinated water transferred to other zones (WT) and daily desalinated water produced (Q)

Zone	Variable	Value	To	Time block																							
				0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Z1	WQ (m^3)			327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327
	WTC (m^3)			27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27
	WT (m^3)		Z2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Q (m^3/day)	8,500																									
Z2	WQ (m^3)			1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265
	WTC (m^3)			84	84	84	84	84	84	84	15	152	84	84	84	15	84	84	152	84	84	84	84	84	84	84	84
	WT (m^3)		Z1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Z3	69	69	69	69	69	69	69	138	0	69	69	69	138	69	69	0	69	69	69	69	69	69	69	69
	Q (m^3/day)	34,000																									

Table A.7- (cont'd)

Zone	**Variable**	**Value**	**To**	**Time block**																							
				0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Z3	WQ (m^3)			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WTC (m^3)			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WT (m^3)		Z2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Z4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Q (m^3/day)	0																									
Z4	WQ (m^3)			3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,706	3,775	3,775	3,775	3,775	3,775	3,775	3,706	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775
	WTC (m^3)			0	0	0	0	0	0	0	69	0	0	0	0	69	0	0	0	0	0	0	0	0	0	0	0
	WT (m^3)		Z3	1,188	1,188	1,188	1,188	1,188	1,188	1,188	1,119	1,256	1,188	1,188	1,188	1,119	1,188	1,188	1,256	1,188	1,188	1,188	1,188	1,188	1,188	1,188	1,188
	Q (m^3/day)	119,000																									

Table A.8- Optimal solution for water supply operation at the point of demand in each zone during summer in semi-flexible scenario, including water assigned directly from desalination plant (WQ), desalinated water transferred from other zones (WT) and desalinated water assigned from storage tank (WV)

Zone	**Variable**	**From**	**Time block**																							
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Z1	WQ (m^3)		327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327
	WT (m^3)	Z2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WV (m^3)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Z2	WQ (m^3)		1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265
	WT (m^3)	Z1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Z3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WV (m^3)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A.8- (cont'd)

Zone	**Variable**	**From**	**Time block**																							
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Z3	WQ (m^3)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WT (m^3)	Z2	69	69	69	69	69	69	69	138	0	69	69	69	138	69	69	0	69	69	69	69	69	69	69	69
		Z4	1,188	1,188	1,188	1,188	1,188	1,188	1,188	1,119	1,256	1,188	1,188	1,188	1,119	1,188	1,188	1,256	1,188	1,188	1,188	1,188	1,188	1,188	1,188	1,188
	WV (m^3)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Z4	WQ (m^3)		3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,706	3,775	3,775	3,775	3,775	3,775	3,775	3,706	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775
	WT (m^3)	Z3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WV (m^3)		0	0	0	0	0	0	0	0	69	0	0	0	0	0	0	69	0	0	0	0	0	0	0	0

Table A.9- Surplus PV output fed to the electrical grid (Surp) in each zone 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 in semi-flexible scenario

Zone	**Variable**	**Time block**																							
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Z1	Surp (kWh)[1]	0	0	0	0	0	0	0	0	641	1,759	2,549	2,877	2,971	2,640	1,861	789	0	0	0	0	0	0	0	0
	Re^w (kWh)	0	0	0	0	0	0	0	0	641	1,420	1,420	1,420	1,420	1,420	1,420	789	0	0	0	0	0	0	0	0
	P^w (kWh)	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	779	0	0	0	0	0	0	631	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420
	TD^{ew} (kWh)	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420
Z2	Surp (kWh)	0	0	0	0	0	0	0	0	2,478	6,803	9,860	11,130	11,493	10,211	7,199	3,052	0	0	0	0	0	0	0	0
	Re^w (kWh)	0	0	0	0	0	0	0	0	2,478	5,689	5,689	5,689	5,701	5,689	5,689	3,052	0	0	0	0	0	0	0	0
	P^w (kWh)	5,689	5,689	5,689	5,689	5,689	5,689	5,689	5,701	3,199	0	0	0	0	0	0	2,626	5,689	5,689	5,689	5,689	5,689	5,689	5,689	5,689
	TD^{ew} (kWh)	5,689	5,689	5,689	5,689	5,689	5,689	5,689	5,701	5,678	5,689	5,689	5,689	5,701	5,689	5,689	5,678	5,689	5,689	5,689	5,689	5,689	5,689	5,689	5,689

Table A.9- (cont'd)

Zone	**Variable**	**Time block**																							
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Z3	Surp (kWh)	0	0	0	0	0	0	0	0	2,461	6,755	9,791	11,051	11,411	10,138	7,148	3,030	0	0	0	0	0	0	0	0
	Re^w (kWh)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	P^w (kWh)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	TD^{ew} (kWh)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Z4	Surp (kWh)	0	0	0	0	0	0	0	11,571	25,494	39,387	49,092	53,558	55,415	52,334	44,254	32,978	17,243	2,037	0	0	0	0	0	0
	Re^w (kWh)	0	0	0	0	0	0	0	11,571	20,091	20,078	20,078	20,078	20,073	20,078	20,078	20,091	17,243	2,037	0	0	0	0	0	0
	P^w (kWh)	20,078	20,078	20,078	20,078	20,078	20,078	20,078	8,502	0	0	0	0	0	0	0	0	2,835	18,041	20,078	20,078	20,078	20,078	20,078	20,078
	TD^{ew} (kWh)	20,078	20,078	20,078	20,078	20,078	20,078	20,078	20,073	20,091	20,078	20,078	20,078	20,073	20,078	20,078	20,091	20,078	20,078	20,078	20,078	20,078	20,078	20,078	20,078

[1] In cases where there is no water-related electricity demand or its amount is less than surplus PV output, it is consumed by existing load from households not equipped with PV systems.

6. Tables of optimal solution for fixed scenario

Table A.10- Optimal solution for water supply operation at the point of production in each zone during summer in fixed scenario, including water assigned directly from desalination plant (WQ), water pushed for storage from desalination plant (WTC), desalinated water transferred to other zones (WT) and daily desalinated water produced (Q)

Zone	Variable	Value	To	Time block																							
				0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Z1	WQ (m^3)			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WTC (m^3)			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WT (m^3)		Z2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Q (m^3/day)	0																									
Z2	WQ (m^3)			1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265
	WTC (m^3)			465	465	465	465	465	465	465	328	534	534	465	0	0	87	534	534	465	465	465	465	465	465	465	465
	WT (m^3)		Z1	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327
			Z3	69	69	69	69	69	69	69	206	0	0	69	534	534	447	0	0	69	69	69	69	69	69	69	69
	Q (m^3/day)	51,000																									

Table A.10- (cont'd)

Zone	**Variable**	**Value**	**To**	**Time block**																							
				0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Z3	WQ (m^3)			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WTC (m^3)			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WT (m^3)		Z2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Z4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Q (m^3/day)	0																									
Z4	WQ (m^3)			3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,706	3,706	3,775	3,775	3,775	3,775	3,706	3,706	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775
	WTC (m^3)			0	0	0	0	0	0	0	138	0	0	0	465	465	378	0	0	0	0	0	0	0	0	0	0
	WT (m^3)		Z3	1,188	1,188	1,188	1,188	1,188	1,188	1,188	1,050	1,256	1,256	1,188	722	722	809	1,256	1,256	1,188	1,188	1,188	1,188	1,188	1,188	1,188	1,188
	Q (m^3/day)	119,000																									

Table A.11- Optimal solution for water supply operation at the point of demand in each zone during summer in fixed scenario, including water assigned directly from desalination plant (WQ), desalinated water transferred from other zones (WT) and desalinated water assigned from storage tank (WV)

Zone	**Variable**	**From**	**Time block**																							
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Z1	WQ (m^3)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WT (m^3)	Z2	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327
	WV (m^3)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Z2	WQ (m^3)		1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265	1,265
	WT (m^3)	Z1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Z3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WV (m^3)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A.11- (cont'd)

Zone	**Variable**	**From**	**Time block**																							
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Z3	WQ (m^3)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WT (m^3)	Z2	69	69	69	69	69	69	69	206	0	0	69	534	534	447	0	0	69	69	69	69	69	69	69	69
		Z4	1,188	1,188	1,188	1,188	1,188	1,188	1,188	1,050	1,256	1,256	1,188	722	722	809	1,256	1,256	1,188	1,188	1,188	1,188	1,188	1,188	1,188	1,188
	WV (m^3)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Z4	WQ (m^3)		3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,706	3,706	3,775	3,775	3,775	3,775	3,706	3,706	3,775	3,775	3,775	3,775	3,775	3,775	3,775	3,775
	WT (m^3)	Z3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WV (m^3)		0	0	0	0	0	0	0	0	69	69	0	0	0	0	69	69	0	0	0	0	0	0	0	0

Table A.12- Surplus PV output fed to the electrical grid (Surp) in each zone 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 in fixed scenario

Zone	**Variable**	**Time block**																							
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Z1	Surp (kWh)[1]	0	0	0	0	0	0	0	0	641	1,759	2,549	2,877	2,971	2,640	1,861	789	0	0	0	0	0	0	0	0
	Re^w (kWh)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	P^w (kWh)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	TD^{ew} (kWh)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Z2	Surp (kWh)	0	0	0	0	0	0	0	0	2,478	6,803	9,860	11,130	11,493	10,211	7,199	3,052	0	0	0	0	0	0	0	0
	Re^w (kWh)	0	0	0	0	0	0	0	0	2,478	6,803	8,621	8,700	8,700	8,685	7,199	3,052	0	0	0	0	0	0	0	0
	P^w (kWh)	8,621	8,621	8,621	8,621	8,621	8,621	8,621	8,644	6,131	1,806	0	0	0	0	1,411	5,558	8,621	8,621	8,621	8,621	8,621	8,621	8,621	8,621
	TD^{ew} (kWh)	8,621	8,621	8,621	8,621	8,621	8,621	8,621	8,644	8,609	8,609	8,621	8,700	8,700	8,685	8,609	8,609	8,621	8,621	8,621	8,621	8,621	8,621	8,621	8,621

Table A.12- (cont’d)

Zone	**Variable**	**Time block**																							
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Z3	Surp (kWh)	0	0	0	0	0	0	0	0	2,461	6,755	9,791	11,051	11,411	10,138	7,148	3,030	0	0	0	0	0	0	0	0
	Re^w (kWh)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	P^w (kWh)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	TD^{ew} (kWh)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Z4	Surp (kWh)	0	0	0	0	0	0	0	11,571	25,494	39,387	49,092	53,558	55,415	52,334	44,254	32,978	17,243	2,037	0	0	0	0	0	0
	Re^w (kWh)	0	0	0	0	0	0	0	11,571	20,091	20,091	20,078	20,047	20,047	20,052	20,091	20,091	17,243	2,037	0	0	0	0	0	0
	P^w (kWh)	20,078	20,078	20,078	20,078	20,078	20,078	20,078	8,497	0	0	0	0	0	0	0	0	2,835	18,041	20,078	20,078	20,078	20,078	20,078	20,078
	TD^{ew} (kWh)	20,078	20,078	20,078	20,078	20,078	20,078	20,078	20,068	20,091	20,091	20,078	20,047	20,047	20,052	20,091	20,091	20,078	20,078	20,078	20,078	20,078	20,078	20,078	20,078

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[1] In cases where there is no water-related electricity demand or its amount is less than surplus PV output, it is consumed by existing load from households not equipped with PV systems.

References

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[3] Department of Transportation and Environmental Services (T&ES), city of Alexandria. CSS long term control plan, alternatives evaluation: storage tanks, https://www.alexandriava.gov/uploadedFiles/tes/oeq/info/LTCPU%20Storage%20Alternative-FINAL.pdf; 2015 [accessed 9 July 2017].

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A1.2. Supporting document for Chapter 5

I. Mathematical formulation

The two-level optimisation model has been developed essentially on the foundation of the previous studies [1, 2]. The following sections present the mathematical formulation of the model. In description of the equations, the term “time period” refers to the year (t), season (s) and time block (b).

1. Level-one optimisation

1.1. Objective function

The model consists of two objective functions. The objective function in the first stage (z_1) is to maximise the economic benefit from installed PV systems for the householders equipped with rooftop PVs through the savings from avoiding grid electricity usage as well as revenues achieved from surplus PV output fed to the grid (Eq. (A.1)):

$$Max\ z_1 = \left[\sum_t \frac{1}{(1+rr)^{n_t}} \sum_i \sum_s nd_s . \sum_b C^{er}_{t,s,b} . RE^r_{t,i,s,b} + C^{rb}_t . Surp_{t,i,s,b} \right] \tag{A.1}$$

Where, rr (%) is the discount rate for residential sector, n_t is the number of the year and nd_s (day) is the number of days in each season. $C^{er}_{t,s,b}$ and C^{rb}_t (\$/ kWh) are associated with grid electricity tariff for residential sector and feed-in tariff, respectively. Finally, $RE^r_{t,i,s,b}$ and $Surp_{t,i,s,b}$ (kWh) represent, in order, the share of renewable energy in meeting residential electricity demand equipped with PV systems, and surplus PV output fed to the grid.

1.2. Electricity balance for households equipped with PVs

In each zone and time period, the electricity balance for households equipped with PV systems is given by Eq. (A.2):

$$P^r_{t,i,s,b} + RE^r_{t,i,s,b} = k_{t,i} . D^{er}_{t,i,s,b} \qquad \forall t,i,s,b \tag{A.2}$$

Where $P^r_{t,i,s,b}$ (kWh) is the share of grid electricity in satisfying residential electricity demand equipped with PV systems, $k_{t,i}$ (%) refers to the PV installation density and $D^{er}_{t,i,s,b}$ (kWh) is the residential electricity demand.

Increase in the share of grid electricity and renewable energy to satisfy the residential electricity demand over the planning horizon are expressed by Eqs. (A.3) and (A.4):

$$P^r_{t,i,s,b} = P^r_{t-1,i,s,b} + addP^r_{t,i,s,b} \qquad \forall t,i,s,b \tag{A.3}$$

$$RE^{r}_{t,i,s,b} = RE^{r}_{t-1,i,s,b} + addRE^{r}_{t,i,s,b} \quad \forall t,i,s,b \tag{A.4}$$

Where $addP^{r}_{t,i,s,b}$ and $addRE^{r}_{t,i,s,b}$ (kWh) are the added share of each energy source, in order, grid electricity and renewable energy, in meeting the residential electricity demand equipped with PV systems in each year over the planning horizon.

1.3. Energy resources capacities

For each zone and time period, the upper bound of grid electricity allocated to the residential electricity demand equipped with PV systems is given by (Eq. (A.5):

$$P^{r}_{t,i,s,b} \le dur_{b}.MaxPS_{t,i} \quad \forall t,i,s,b \tag{A.5}$$

In which, $MaxPS_{t,i}$ (kW) is the maximum capacity of the zone substations and dur_{b} (h) is the duration of the time block b .

Similarly, the amount of PV output assigned to the households equipped with this system is limited by the maximum potential PV output ($MaxR_{t,i,s,b}$ (kWh)) (Eq. (A.6)):

$$RE^{r}_{t,i,s,b} \le MaxR_{t,i,s,b} \quad \forall t,i,s,b \tag{A.6}$$

1.4. Maximum potential PV output

The maximum potential PV output in each zone and time period (Eqs. (A.7) and (A.8)) are associated with the PV installation density, the performance of a PV system $PV_{s,b}$(kW) and the number of existing rooftops ($exisR_{t,i}$).

$$MaxR_{t,i,s,b} = k_{t,i}.dur_{b}.PV_{s,b}.exisR_{t,i} \quad \forall t,i,s,b \tag{A.7}$$

$$MaxR_{t,i,s,b} = MaxR_{t-1,i,s,b} + addk_{t,i}.k^{p}_{t}.dur_{b}.PV_{s,b}.\left(exisR_{t,i} - exisR_{t-1,i}\right) \quad \forall t,i,s,b \tag{A.8}$$

In Eq. (A.8), $addk_{t,i}$ (%) and k^{p}_{t} are the added PV installation density and the subjectivity-economic index, respectively.

1.5. Surplus PV output

The surplus PV output ($Surp_{t,i,s,b}$(kWh)) that can be potentially assigned to water-related electricity demand and households not equipped with PV systems is calculated based on Eq. (A.9):

$$Surp_{t,i,s,b} = MaxR_{t,i,s,b} - RE^{r}_{t,i,s,b} \quad \forall t,i,s,b \tag{A.9}$$

2. Level-two optimisation

The outcome of the level-one optimisation, namely the PV installation density ($k_{t,i}$ (%)), grid electricity assigned to households equipped with PV systems ($P^{r}_{t,i,s,b}$ (kWh)) and surplus PV output fed to the electrical grid ($Surp_{t,i,s,b}$ (kWh)), are introduced to the second level of optimisation. They are then applied to determine the capacity of each electricity source that can be potentially assigned to the water-related electricity demand and households not equipped with PV systems. The model constraints at level-two optimisation are described in the following sections.

2.1. Objective function

In level- two optimisation, the strategic and operational decisions of the desalinated-based water supply system is determined such that the maximum compatibility with available renewable energy is achieved. The objective function at this level of optimisation (z_2) is to minimise the discounted total cost of the water supply system as given by Eq. (A.10):

$$Min\ z_2 = \underbrace{CCDQ + CCSN + CCWT}_{Discounted\ Capital\ Cost} + \overbrace{OCDQ + OCSN + OCWT + FOC}^{Discounted\ Operational\ and\ Maintenance\ (O\&M)\ Cost} \tag{A.10}$$

In level-two objective function, the first and second terms represent the discounted capital cost and discounted O&M costs of the water supply system over the planning horizon, respectively. Details of the total costs of the system are as follows:

- Eqs. (A.11)-(A.13) present the capital costs of desalination plants ($CCDQ$ (\$)), storage tanks ($CCSN$ (\$)), and pipelines ($CCWT$ (\$)):

$$CCDQ = \sum_t \frac{1}{(1+r)^{n_t - cltDQ}} \sum_i \sum_c CapDQ_{t,c}.XW_{t,i,c} \tag{A.11}$$

$$\begin{aligned} CCSN = {} & \sum_t \frac{1}{(1+r)^{n_t - cltSN}} \sum_i \sum_m CapSN_{t,m}.X_{t,i,m} \\ & + \sum_t \frac{1}{(1+r)^{n_t - cltWT}} \sum_i \sum_j \sum_{pi} CapWT_{t,pi}.np_{t,pi,i}.L_{i,j}.convf_2 \quad \forall (i,j) \in \{L^{w}_{i,j} \mid i = j\} \end{aligned} \tag{A.12}$$

$$\begin{aligned} CCWT = {} & \sum_t \frac{1}{(1+r)^{n_t - cltWT}} \sum_i \sum_j \sum_{pi} CapWT_{t,pi}.npIJ_{t,pi,i,j}.L_{i,j}.convf_2 \\ & \forall (i,j) \in \{L^{w}_{i,j} \mid i \neq j\} \end{aligned} \tag{A.13}$$

Where, r (%) and clt are the weighted average cost of capital (WACC) for water supplier and construction lead time for each water supply component, respectively. In Eq. (A.11),

$CapDQ_{t,c}$ (\$) is the capital cost of a desalination plant at capacity breakpoint c and $XW_{t,i,c}$ is a binary variable, associated with desalination plants capacity. In Eq. (A.12), $CapSN_{t,m}$ is the capital cost of a storage tank at capacity breakpoint m and the binary variable of $X_{t,i,m}$, relates to the capacity of storage tanks. In Eqs. (A.12) and (A.13), $CapWT_{t,pi}$ is the capital cost per unit length of a pipeline at capacity breakpoint pi. The binary variable of $np_{t,pi,i}$ corresponds to the construction or expansion capacity of the pipeline from which extra desalinated water is transferred to the storage tank and $npIJ_{t,pi,i,j}$ represents the decision for installing or expanding the capacity of the pipeline connecting zone i to j. $L_{i,j}$ (m) is the distance from the desalination plant to the storage tank within zone i (where $i = j$), and $convf_2$ (km/m) is the conversion factor.

- O&M costs associated with each component of the water supply system, desalination plants ($OCDQ$ (\$)), water storage ($OCSN$ (\$)), and water transfer ($OCWT$ (\$)) are expressed by Eqs. (A.14)-(A.16):

$$OCDQ = \sum_t \frac{1}{(1+r)^{n_t}} \sum_i \sum_s nd_s . \sum_b C^{eb}_{t,s,b} . P^{wDQ}_{t,i,s,b} + C^{rb}_t . RE^{wDQ}_{t,i,s,b} + C^{OM}_t . Q_{t,i,s,b} \tag{A.14}$$

$$CCSN = \sum_t \frac{1}{(1+r)^{n_t}} \sum_i \sum_s nd_s . \sum_b C^{eb}_{t,s,b} . P^{wSN}_{t,i,s,b} + C^{rb}_t . RE^{wSN}_{t,i,s,b} + C^{s}_t . V_{t,i,s,b} \tag{A.15}$$

$$OCWT = \sum_t \frac{1}{(1+r)^{n_t}} \sum_i \sum_s nd_s . \sum_b C^{eb}_{t,s,b} . P^{wWT}_{t,i,s,b} + C^{rb}_t . RE^{wWT}_{t,i,s,b} \tag{A.16}$$

In which, $C^{eb}_{t,s,b}$ (\$/kWh) is associated with the grid electricity tariff for business sector. In Eq. (A.14), $P^{wDQ}_{t,i,s,b}$ 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, C^{OM}_t (\$/ m^3) is the unit cost of water production and $Q_{t,i,s,b}$ (m^3) is the amount of desalinated water produced. In Eq. (A.15), $P^{wSN}_{t,i,s,b}$ (kWh) 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, C^{s}_t (\$/ m^3) and $V_{t,i,s,b}$ (m^3) are in order, the unit cost of water storage and the existing desalinated water in the storage tank. Lastly, in Eq. (A.16), $P^{wWT}_{t,i,s,b}$ 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 corresponding to the daily electricity charge for operation of the water supply system (FOC (\$)) is described according to Eq. (A.17):

$$FOC = \sum_t \frac{1}{(1+r)^{n_t}} \sum_s C_t^{feb}.nd_s \tag{A.17}$$

Where, C_t^{feb} (\$/day) is the fixed daily electricity charge for business sector in year t .

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)) and the desalinated water assigned from the storage tank ($WV_{t,i,s,b}$ (m^3)) located in the same zone, plus the transferred water from other zones ($WT_{t,j,i,s,b}$ (m^3)) need to fully satisfy water demand ($D_{t,i,s,b}^{w}$ (m^3)) (Eq. (A.18)):

$$WQ_{t,i,s,b} + WV_{t,i,s,b} + \sum_{j:(i,j)\in\{L_{i,j}^{w} | i\neq j\}} WT_{t,j,i,s,b} = D_{t,i,s,b}^{w} \quad \forall t,i,s,b \tag{A.18}$$

2.3. Desalination plants capacities

In each time period, the capacity of a desalination plant located at zone i ($DQ_{t,i}$ (m^3/day)) is given by Eq. (A.19):

$$DQ_{t,i} = DQ_{t-1,i} + DQ_{t,i}^{\exp} \quad \forall t,i \tag{A.19}$$

Where,

$$DQ_{t,i}^{\exp} = \sum_c AC_c.XW_{t,i,c} \quad \forall t,i \tag{A.20}$$

$$\sum_c XW_{t,i,c} \leq 1 \quad \forall t,i \tag{A.21}$$

Eq. (A.20), determines the expansion capacity of a desalination plant at zone i and in year t ($DQ_{t,i}^{\exp}$ (m^3/day)) selected from c discrete values (AC_c (m^3/day)) and Eq. (A.21) ensures that at most one capacity expansion occurs in each year over the planning horizon.

The upper bound of desalinated water production ($Q_{t,i,s,b}$ (m^3)) is also expressed by Eq. (A.22):

$$\sum_s nd_s.\sum_b Q_{t,i,s,b} \leq PF.\sum_s DQ_{t,i}.nd_s \quad \forall t,i \tag{A.22}$$

Where PF is the plant factor.

2.4. Storage tanks capacities

Eq. (A.23) specifies the capacity of a storage tank in each zone and year ($SN_{t,i}$ (m^3)):

$$SN_{t,i} = SN_{t-1,i} + SN_{t,i}^{\exp} \quad \forall t, i \tag{A.23}$$

In which

$$SN_{t,i}^{\exp} = \sum_{m} ST_m . X_{t,i,m} \quad \forall t, i \tag{A.24}$$

The expansion capacity of $SN_{t,i}^{\exp}$ (m^3) can be chosen from m discrete values (ST_m (m^3)) (Eq. (A.24)).

Zone i can be only equipped with a storage tank if a desalination plant (with any capacity) is placed in the same zone (Section 2.1 of the main manuscript). At the same time, at most one storage tank capacity expansion can occur in each year during the planning horizon. Both constraints can be summarised in Eq. (A.25):

$$\sum_{m} X_{t,i,m} \le \sum_{c} XW_{t,i,c} \quad \forall t, i \tag{A.25}$$

The expansion capacity of the storage tank in each zone and time period is constrained by minimum and maximum allowable storage tank capacity corresponding to the desalination plant at capacity breakpoint c ($MinS_c$ and $MaxS_c$ (m^3)) (Eqs. (A.26) and (A.27)):

$$SN_{t,i}^{\exp} \ge \sum_{c} MinS_c . XW_{t,i,c} \quad \forall t, i \tag{A.26}$$

$$SN_{t,i}^{\exp} \le \sum_{c} MaxS_c . XW_{t,i,c} \quad \forall t, i \tag{A.27}$$

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 the desalination plant in zone i to meet the demand in the same zone and the amount transferred from zone i to other zones (Eq. (A.28)). $WTC_{t,i,s,b}$ is also limited to the capacity of the pipeline connecting the desalination plant to the storage tank within zone i ($capPI_{t,i}$(m^3/day)) (Eq. (A.29)):

$$WTC_{t,i,s,b} = Q_{t,i,s,b} - WQ_{t,i,s,b} - \sum_{j:(i,j)\in\{L_{i,j}^{w} | i \ne j\}} WT_{t,i,j,s,b} \quad \forall t, i, s, b \tag{A.28}$$

$$WTC_{t,i,s,b} \le convf_1.capPI_{t,i}.dur_b \quad \forall t,i,s,b \tag{A.29}$$

Where $convf_1$ (day/h) is a conversion factor.

The capacity of the connecting pipeline between the desalination plant and the storage tank within the same zone is determined according to Eq. (A.30).

$$capPI_{t,i} = capPI_{t-1,i} + capPI_{t,i}^{\exp} \quad \forall t,i \tag{A.30}$$

In each zone and year, the expansion capacity of the pipeline ($capPI_{t,i}^{\exp}$(m^3/day)) can be selected from pi discrete values (Eq. (A.31)):

$$capPI_{t,i}^{\exp} = \sum_{pi} PipeL_{pi}.np_{t,pi,i} \quad \forall t,i \tag{A.31}$$

Where, $PipeL_{pi}$ (m^3/day) is the capacity of the pipeline at capacity breakpoint pi.

2.6. Desalinated water storage

In each time period, the existing desalinated water in the storage tank at 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. (A.32):

$$V_{t,i,s,b} = V_{t,i,s,b-1} + WTC_{t,i,s,b} - WV_{t,i,s,b} \quad \forall t,i,s,b \tag{A.32}$$

In each time period, $V_{t,i,s,b}$ is limited to the capacity of the storage tank selected for zone i (Eq. (A.33)). Also, $WV_{t,i,s,b}$ cannot exceed the amount of existing desalinated water in the storage tank from the previous time block (Eq. (A.34)):

$$V_{t,i,s,b} \le SN_{t,i} \quad \forall t,i,s,b \tag{A.33}$$

$$WV_{t,i,s,b} \le V_{t,i,s,b-1} \quad \forall t,i,s,b \tag{A.34}$$

2.7. Water flows

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 capacity of the associated connecting pipeline ($capPIJ_{t,i,j}$ (m^3/day)) (Eq. (A.35)):

$$WT_{t,i,j,s,b} \le convf_1.capPIJ_{t,i,j}.dur_b \quad \forall t,s,b,(i,j) \in \{L_{i,j}^{w} | i \ne j\} \tag{A.35}$$

The capacity of the pipeline connecting zone i to zone j is defined by Eqs. (A.36) and (A.37):

$$capPIJ_{t,i,j} = capPIJ_{t-1,i,j} + capPIJ^{\exp}_{t,i,j} \qquad \forall t,(i,j) \in \{L^{w}_{i,j} | i \neq j\} \tag{A.36}$$

Where the expansion capacity of the connecting pipeline can be chosen from pi discrete values (Eq. (A.37)):

$$capPIJ^{\exp}_{t,i,j} = \sum_{pi} PipeL_{pi}.npIJ_{t,pi,i,j} \qquad \forall t,(i,j) \in \{L^{w}_{i,j} | i \neq j\} \tag{A.37}$$

Eq. (A.38), guarantees that the simultaneous reverse flow of water through the same pair of allowable zones does not occur.

$$npIJ_{t,pi,i,j} + npIJ_{t,pi,j,i} \leq 1 \qquad \forall t, pi, (i,j) \in \{L^{w}_{i,j} | i \neq j\} \tag{A.38}$$

2.8. Water-related electricity balance

Eqs. (A.39)-(A.41) determine water-related electricity balance corresponding to water production, storage, and transfer for each zone and time period, respectively:

$$P^{wDQ}_{t,i,s,b} + RE^{wDQ}_{t,i,s,b} = Q_{t,i,s,b}.D^{ep} \qquad \forall t,i,s,b \tag{A.39}$$

$$P^{wSN}_{t,i,s,b} + RE^{wSN}_{t,i,s,b} = \sum_{j:(i,j)\in\{PL^{w}_{i,j} | i=j\}} WTC_{t,i,s,b}.D^{ewt}_{i,j} \qquad \forall t,i,s,b \tag{A.40}$$

$$P^{wWT}_{t,i,s,b} + RE^{wWT}_{t,i,s,b} = \sum_{j:(i,j)\in\{PL^{w}_{i,j} | i\neq j\}} WT_{t,i,j,s,b}.D^{ewt}_{i,j} \qquad \forall t,i,s,b \tag{A.41}$$

Therein, D^{ep} and $D^{ewt}_{i,j}$ (kWh/m^3) are, in order, the electricity demand per unit of water produced and transferred. In Eqs. (A.40) and (A.41), $PL^{w}_{i,j}$ 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. (A.42)):

$$P^{w}_{t,i,s,b} + RE^{w}_{t,i,s,b} = TD^{ew}_{t,i,s,b} \qquad \forall t,i,s,b \tag{A.42}$$

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)).

3. Common constraints between two levels of optimisation

3.1. Electricity balance for households not equipped with PVs

In each zone and time period, the electricity balance between electricity demand for households, which are not equipped with PV system $(1-k_{t,i}).D^{er}_{t,i,s,b}$(kWh)) and electricity sources is given by Eq. (A.43):

$$P^{rn}_{t,i,s,b} + RE^{rn}_{t,i,s,b} = (1-k_{t,i}).D^{er}_{t,i,s,b} \quad \forall t,i,s,b \tag{A.43}$$

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.

3.2. Energy resources capacity

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 the associated zone substations (Eq. (A.44)). Moreover, the share of renewable energy in supplying the electricity demand should be such that no unused surplus PV output remains (Eq. (A.45)).

$$P^{rn}_{t,i,s,b} + P^{w}_{t,i,s,b} + P^{r}_{t,i,s,b} \le dur_b.MaxPS_{t,i} \quad \forall t,i,s,b \tag{A.44}$$

$$Surp_{t,i,s,b} - RE^{rn}_{t,i,s,b} + RE^{w}_{t,i,s,b} \le \varepsilon \quad \forall t,i,s,b \tag{A.45}$$

Where ε is a very small number close to zero.

4. Specific constraints for BAU and CGPV scenarios

4.1. Additional constraint for BAU and CGPV scenarios

Considering the centralised water supply system in BAU and CGPV scenarios, the location of the sole desalination plant can be dictated according to Eq. (A.46):

$$DQ_{t,i} \le Ac^{\max}_{i} \quad \forall t,i \tag{A.46}$$

Where $Ac^{\max}_{i}$ (m^3/day), is the allowable capacity of the largest desalination plant can be located at each zone.

Additionally, in BAU scenario, the renewable energy does not contribute to providing water-related energy demand in any year over the planning horizon. Eq. (A.47) ensures this constraint.

$$RE^{w}_{t,i,s,b} = 0 \quad \forall t,i,s,b \tag{A.47}$$

4.2. Modification of constraints common among all scenarios

The equations described in Sections 1-3 of this supplementary are related to DGPV scenario. In this section, the equivalent constraints corresponding to the fixed operational mode of the water supply system in BAU and CGPV scenarios versus flexible operational scheduling in DGPV scenario are presented as follows:

Eq. (A.48) represents the discounted O&M costs of desalination plants, equivalent to Eq. (A.14) in Section 2.1 of this supplementary:

$$OCDQ = \sum_t \frac{1}{(1+r)^{n_t}} \sum_i \sum_s nd_s . \sum_b C^{eb}_{t,s,b} . P^{wDQ}_{t,i,s,b} + C^{rb}_t . RE^{wDQ}_{t,i,s,b} + \sum_s C^{OM}_t . Q_{t,i} . nd_s \tag{A.48}$$

Eq. (A.49) expresses the upper bound of desalinated water produced, equivalent to Eq. (A.22) in Section 2.3 of this supplementary:

$$Q_{t,i} = PF.DQ_{t,i} \qquad \forall t,i \tag{A.49}$$

Eq. (A.50) determines the amount of desalinated water pushed for storage, equivalent to Eq. (A.29) in Section 2.5 of this supplementary:

$$WTC_{t,i,s,b} = convf_1 . Q_{t,i} - WQ_{t,i,s,b} - \sum_{j:(i,j)\in\{L^w_{i,j} | i\neq j\}} WT_{t,i,j,s,b} \qquad \forall t,i,s,b \tag{A.50}$$

Eq. (A.51) gives water-related electricity balance corresponding to water production, equivalent to Eq. (A.39) in Section 2.8 of this supplementary:

$$P^{wDQ}_{t,i,s,b} + RE^{wDQ}_{t,i,s,b} = convf_1 . Q_{t,i} . D^{ep} \qquad \forall t,i,s,b \tag{A.51}$$

Nomenclature

Sets

b	time block
c	set of discrete points of desalination plants capacity
i, j	zone
$L^{w}_{i,j}$	allowable zones (i, j) for water transfer
m	set of discrete points of storage tanks capacity
n_t	number of the year
pi	set of discrete points of pipeline capacity
$PL^{w}_{i,j}$	allowable zones (i, j) for water transfer where pumping is needed
s	season
t	set of years in the planning horizon

Parameters

AC_c	capacity of desalination plant at capacity breakpoint c (m^3/day)
$Ac_i^{\max}$	capacity of the largest plant could be built in zone i (m^3/day) (used in BAU and CGPV scenarios)
$C^{eb}_{t,s,b}$	variable electricity charge for business sector per unit of grid electricity usage in year 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 year t, season s and time block b (\$/kWh)
C^{rb}_{t}	variable electricity charge for business sector per unit of renewable energy usage in year t (\$/kWh)
C^{feb}_{t}	fixed daily electricity charge for business sector in year t (\$/day)
C^{OM}_{t}	average desalination plants O&M cost per unit of water production in year t (\$/m^3)
C^{s}_{t}	average O&M cost per unit of stored desalinated water in year t (\$/m^3)
$CapDQ_{t,c}$	capital cost of the desalination plant at capacity breakpoint c and year t (\$)
$CapSN_{t,m}$	capital cost of storage tank at capacity breakpoint m and year t (\$)
$CapWT_{t,pi}$	capital cost per unit length of pipeline at capacity breakpoint pi and year t (\$/km)
$cltDQ$	Construction lead time for desalination plant in terms of the number of the years
$cltSN$	Construction lead time for storage tank in terms of the number of the years
$cltWT$	Construction lead time for pipeline network in terms of the number of the years
$convf_1$	conversion factor (day/h)
$convf_2$	conversion factor (km/m)
$D^{er}_{t,i,s,b}$	residential energy demand in zone i year t season s and time block b (kWh)
$D^{w}_{t,i,s,b}$	water demand in zone i year 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)
$exisR_{t,i}$	the number of existing residential rooftops in zone i and year t
k^{p}_{t}	The product of the economic and subjectivity indexes (subjectivity-economic index) in each year t
$L_{i,j}$	distance from a desalination plant to a storage tank within zone i or from a desalination

	plant in zone i to the demand centre in zone j (m)
$MaxPS_{t,i}$	maximum capacity of substations in zone i and year t (kW)
$MaxS_c$	maximum allowable storage tank capacity corresponding to the desalination plant at capacity breakpoint c (m^3)
$PipeL_{pi}$	capacity of the pipeline at capacity breakpoint pi (m^3/day)
$MinS_c$	minimum allowable storage tank capacity corresponding to the desalination plant at capacity breakpoint c (m^3)
nd_s	number of days in each season (day)
PF	plant factor
$PV_{s,b}$	PV system output in season s and time block b (kW)
r	weighted average cost of capital (for business sector) (%)
rr	discount rate (for residential sector) (%)
ST_m	capacity of storage tank at capacity breakpoint m (m^3)
ε	A small number close to zero

Continuous variables

$addk_{t,i}$	added PV installation density in zone i and year t (%)
$addP^{r}_{t,i,s,b}$	added share of grid electricity to meet electricity demand of households equipped with PV system in zone i year t season s and time block b (kWh)
$addRE^{r}_{t,i,s,b}$	added share of PV output to meet electricity demand of households equipped with PV system in zone i year t season s and time block b (kWh)
$capPI_{t,i}$	capacity of the pipeline in zone i and year t (m^3/day)
$capPI^{\exp}_{t,i}$	expansion capacity of the pipeline in zone i and year t (m^3/day)
$capPIJ_{t,i,j}$	capacity of the connecting pipeline between zone i and j in year t (m^3/day)
$capPIJ^{\exp}_{t,i,j}$	expansion capacity of the pipeline between zone i and j in year t (m^3/day)
$CCDQ$	capital cost of desalination plants ($)
$CCSN$	capital cost of storage tanks ($)
$CCWT$	capital cost of pipelines ($)
$DQ_{t,i}$	capacity of the desalination plant in zone i and year t (m^3/day)
$DQ^{\exp}_{t,i}$	expansion capacity of the desalination plant in zone i and year t (m^3/day)
FOC	fixed electricity charge for operating water supply system ($)
$k_{t,i}$	PV installation density in zone i and year t (%)
$MaxR_{t,i,s,b}$	maximum potential PV output correspondent to installation density $k_{t,i}$ in zone i year t season s and time block b (kWh)
$OCDQ$	O&M cost of desalination plants ($)
$OCSN$	O&M cost of water storage ($)
$OCWT$	O&M cost of water transfer ($)
$P^{r}_{t,i,s,b}$	share of grid electricity to meet electricity demand of households equipped with PV system in zone i year t 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 year t 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 year t 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 year t 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 year t 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 year t season s and time block b (kWh)
$Q_{t,i,s,b}$	desalinated water produced in zone i year t season s and time bock b (m^3)
$Q_{t,i}$	daily desalinated water produced in zone i and year t (m^3/day) (used in BAU and CGPV scenarios)
$RE^{r}_{t,i,s,b}$	share of PV output to meet electricity demand of households equipped with PV system in zone i year t 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 year t 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 year t 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 year t 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 year t 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 year t season s and time block b (kWh)
$SN_{t,i}$	capacity of the storage tank in zone i and year t (m^3)
$SN^{\exp}_{t,i}$	expansion capacity of the storage tank in zone i and year t (m^3)
$Surp_{t,i,s,b}$	Surplus PV generation at zone i year t season s and time block b (kWh)
$TD^{ew}_{t,i,s,b}$	total water-related energy demand in zone i year t season s and time block b (kWh)
$V_{t,i,s,b}$	existing desalinated water stored in the storage tank in zone i year t 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 in t season s and time block b (m^3)
$WT_{t,i,j,s,b}$	desalinated water transferred from zone i to j in year t season s and time block b (m^3)
$WTC_{t,i,s,b}$	water pushed for storage from desalination plant in zone i year t 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 in year t season s and time block b (m^3)

Binary variables

$np_{t,pi,i}$	1 if construction/ expansion capacity of the pipeline at capacity breakpoint pi occurs in zone i and year t; 0 otherwise
$npIJ_{t,pi,i,j}$	1 if construction/ expansion capacity of the pipeline at capacity breakpoint pi occurs between zone i and j in year t; 0 otherwise

$X_{t,i,m}$	1 if the storage tank at capacity breakpoint m occurs in zone i and year t; 0 otherwise
$XW_{t,i,c}$	1 if the desalination plant at capacity breakpoint c occurs in zone i and year t; 0 otherwise

II. Supplementary input data tables

Table A.1. Average annual estimated water demand for four defined zones within the case study area

Year	Water demand (m^3/year)			
	Z1	Z2	Z3	Z4
2017	2.94E+06	1.14E+07	1.13E+07	3.39E+07
2018	3.02E+06	1.17E+07	1.16E+07	3.48E+07
2019	3.09E+06	1.20E+07	1.19E+07	3.57E+07
2020	3.17E+06	1.23E+07	1.22E+07	3.66E+07
2021	3.26E+06	1.26E+07	1.25E+07	3.76E+07
2022	3.34E+06	1.29E+07	1.28E+07	3.85E+07
2023	3.43E+06	1.33E+07	1.32E+07	3.95E+07
2024	3.52E+06	1.36E+07	1.35E+07	4.06E+07
2025	3.61E+06	1.39E+07	1.38E+07	4.16E+07
2026	3.70E+06	1.43E+07	1.42E+07	4.27E+07
2027	3.79E+06	1.47E+07	1.46E+07	4.38E+07
2028	3.89E+06	1.51E+07	1.50E+07	4.49E+07
2029	3.99E+06	1.54E+07	1.53E+07	4.61E+07
2030	4.10E+06	1.58E+07	1.57E+07	4.73E+07
2031	4.20E+06	1.63E+07	1.61E+07	4.85E+07

Table A.2. Average annual estimated residential energy demand for four defined zones within the case study area

Year	Residential energy demand (kWh/year)			
	Z1	Z2	Z3	Z4
2017	1.04E+08	4.01E+08	3.98E+08	1.20E+09
2018	1.06E+08	4.12E+08	4.09E+08	1.23E+09
2019	1.09E+08	4.22E+08	4.19E+08	1.26E+09
2020	1.12E+08	4.33E+08	4.30E+08	1.29E+09
2021	1.15E+08	4.44E+08	4.41E+08	1.33E+09
2022	1.18E+08	4.56E+08	4.53E+08	1.36E+09
2023	1.21E+08	4.68E+08	4.64E+08	1.39E+09
2024	1.24E+08	4.80E+08	4.76E+08	1.43E+09
2025	1.27E+08	4.92E+08	4.89E+08	1.47E+09
2026	1.31E+08	5.05E+08	5.01E+08	1.51E+09
2027	1.34E+08	5.18E+08	5.14E+08	1.54E+09
2028	1.37E+08	5.31E+08	5.27E+08	1.58E+09
2029	1.41E+08	5.45E+08	5.41E+08	1.63E+09
2030	1.45E+08	5.59E+08	5.55E+08	1.67E+09
2031	1.48E+08	5.74E+08	5.69E+08	1.71E+09

Table A.3- Capacities/sizes, associated capital/unit-installed, and O&M costs for different components of water supply system

Water supply components	**Capacity/size**	**Capital cost($)/ pipeline unit-installed cost ($/km)**	**O&M cost ($/m^3)** [2]
Desalination plant (m^3/day)	20,000	1.18E+08	0.43
	40,000	2.07E+08	0.42
	60,000	3.00E+08	0.39
	80,000	4.03E+08	0.37
	100,000	5.26E+08	0.38
	120,000	5.62E+08	0.34
	280,000	1.26E+09	0.33
Storage tank (m^3)	10,000	3.74E+07	0.13
	20,000	6.42E+07	0.10
Pipe diameter (in)	30[1]	9.93E+04	-
	54	2.96E+06	-

[1] The capacity of pipeline is calculated considering a water velocity of 0.8 m/s.

[2] For all water supply components, the energy cost is calculated directly by the optimisation model based on the energy consumption per unit of desalinated water produced, pumped and transferred as well as the energy source (grid electricity or PV output) assigned to the demand.

Table A.4- Allowable zones (Z) for water transfer in BAU and CGPV scenarios as well as associated distance and pumping elevation

	Distance/pumping elevation (m)			
	Z1	Z2	Z3	Z4
Z1	4,451/8.91	10,922/-	24,663/-	30,315/-
Z2	-	-	-	-
Z3	-	-	-	-
Z4	-	-	-	-

Table A.5- Allowable zones (Z) for water transfer in DGPV scenario as well as associated distance and pumping elevation [1]

	Distance/pumping elevation (m)			
	Z1	Z2	Z3	Z4
Z1	4,451/8.91	10,922/-	-	-
Z2	13,602/27.99	3,073/2.94	16,787/9.79	-
Z3	-	17,955/1.76	8,894/8.61	14,572/13.52
Z4	-	-	16,835/3.97	8,882/8.88

Table A.6- Estimated maximum capacities of zone substations over the planning horizon

	Zone substations capacity (kW)			
	Z1	Z2	Z3	Z4
2017	76,000	152,000	190,000	494,000
2018-2031	76,000	190,000	190,000	494,000

Table A.7- SAM model input data [1]

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 [3]
Azimuth (degree)-subarray 1	300 based on [3]
Azimuth (degree)-subarray 2	60 based on [3]

III. Supplementary results graphs

Figs. A.1- A.6 indicate the optimal operational solution for the representative zone 4 for all scenarios in winter time (for the year 2028).

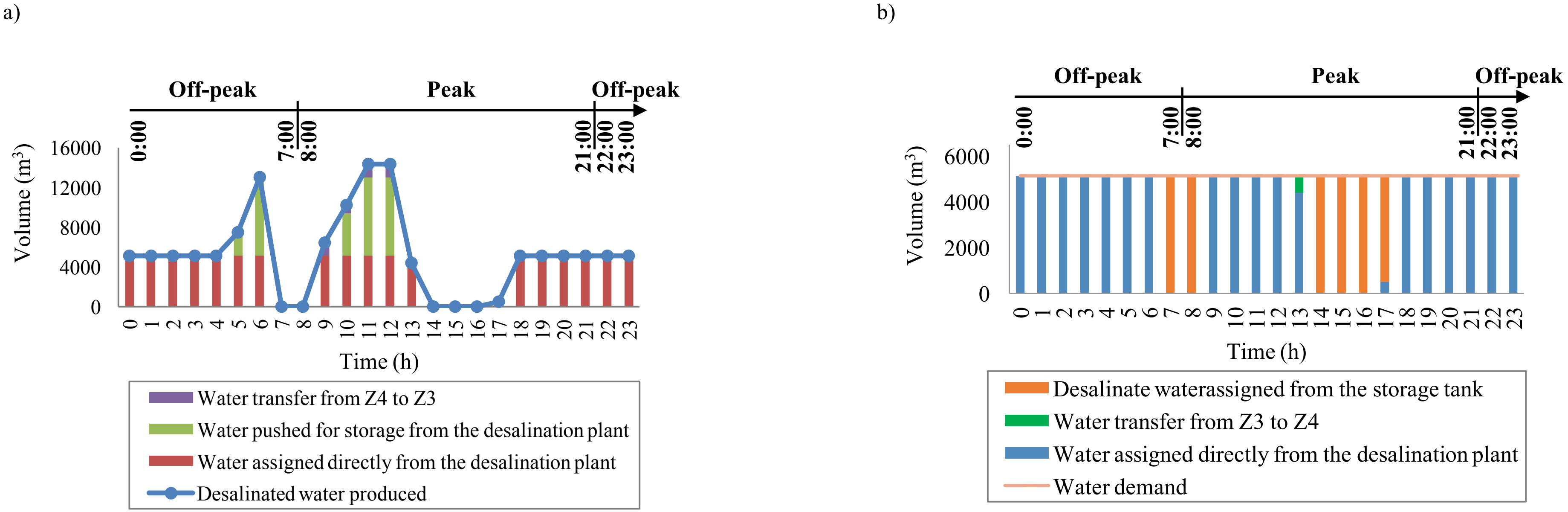


Fig. A.1- The operational scheduling of the water supply system in DGPV scenario: a) at the point production b) at the point of demand

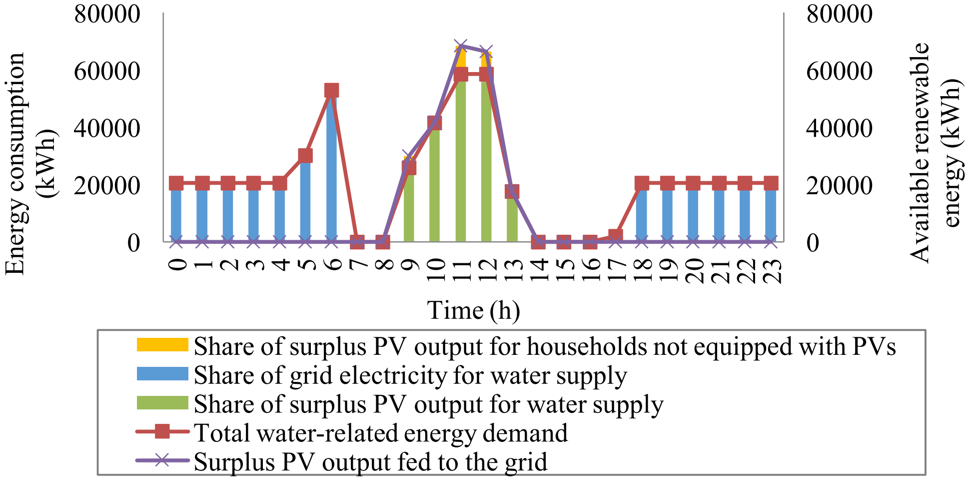


Fig. A.2- Share of each energy source in supplying water-related electricity demand in DGPV scenario

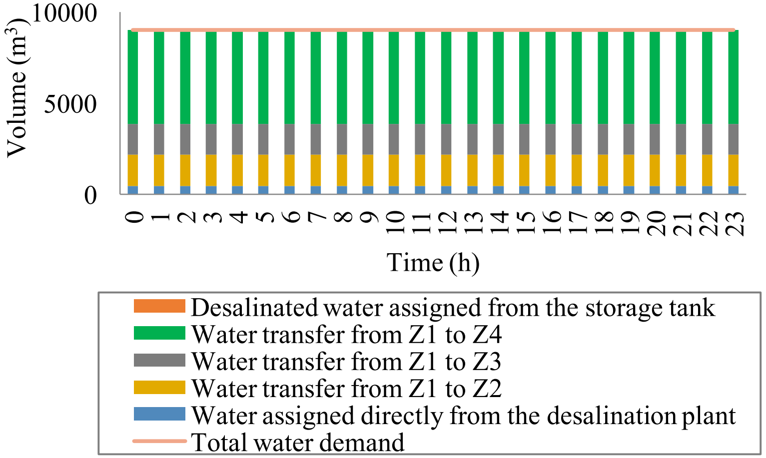
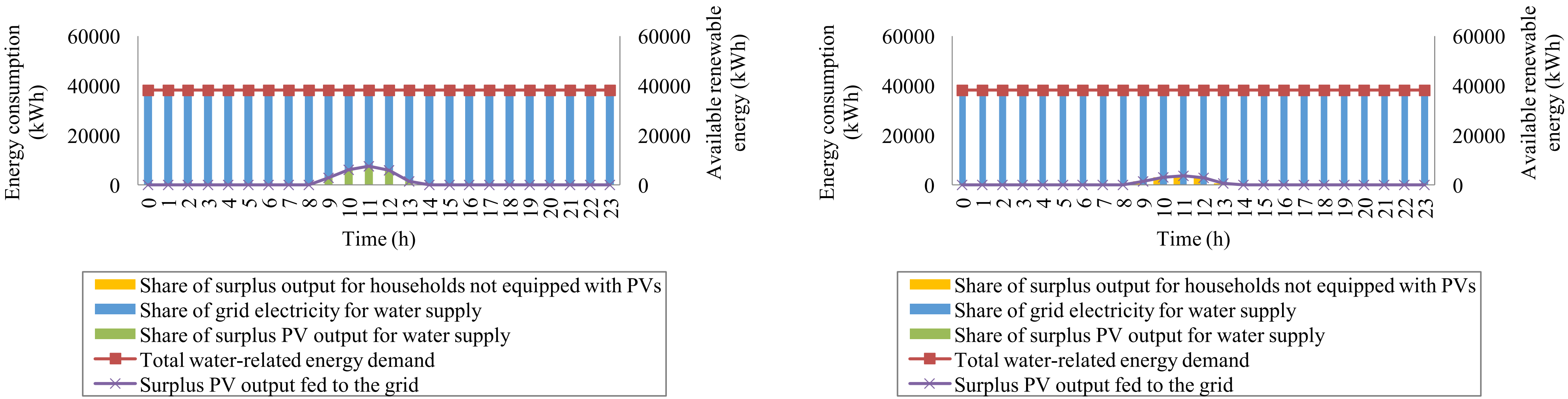


Fig. A.3- The operational scheduling of the water supply system in CGPV and BAU scenarios at the point of production


a)

b)

Fig. A.4- Share of each energy source in supplying water-related electricity demand at the point of production in: a) CGPV and b) BAU scenarios

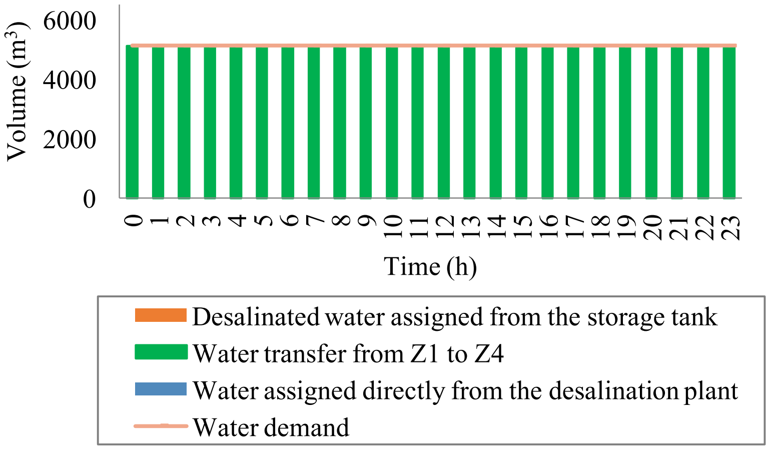


Fig. A.5- The operational scheduling of the water supply system in CGPV and BAU scenarios at the point of demand

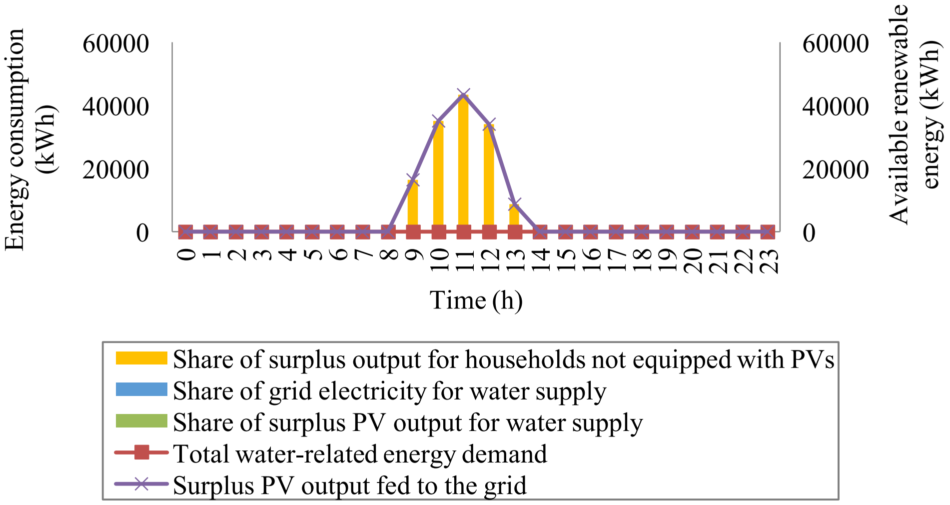


Fig. A.6- Share of each energy source in supplying water-related electricity demand in BAU and CGPV scenarios at the point of demand

References

[1] Vakilifard N, A. Bahri P, Anda M, Ho G. A two-level decision making approach for optimal integrated urban water and energy management. Energy. 2018;155:408-425.

[2] Vakilifard N, A. Bahri P, Anda M, Ho G. Integrating real-time operational constraints in planning of water and energy supply. In: Computer aided process engineering. Elsevier; Forthcoming 2018.

[3] Western Power. Study on the impact of photovoltaic generation on peak demand, https://www.scribd.com/document/318395460/Study-on-the-Impact-of-Photovoltaic-PV-Generation-on-Peak-Demand; 2012 [accessed 31 May 2016].

Appendix 2

In this section, the formatted papers published are presented[1].

A2.1. The role of water-energy nexus in optimising water supply systems– Review of techniques and approaches

Link: https://www.sciencedirect.com/science/article/pii/S1364032117307621

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[1] It is notable that the material in this section has been removed due to copyright restrictions and replaced by the links associated with the original published papers.

A2.2. Water security and clean Energy, co-benefits of an integrated water and energy management

Link: https://www.sciencedirect.com/science/article/pii/B9780444639653502294

A2.3. A two-level decision making approach for optimal integrated urban water and energy management

Link: https://www.sciencedirect.com/science/article/abs/pii/S0360544218308168

A2.4. Integrating real-time operational constraints in planning of water and energy supply

Link: https://www.sciencedirect.com/science/article/pii/B9780444642356500589

A2.5. An interactive planning model for sustainable urban water and energy supply

Link: https://www.sciencedirect.com/science/article/pii/S0306261918316969

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