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Article · January 2017

DOI: 10.1016/j.apenergy.2016.12.142

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## A multi-criteria infrastructure planning framework for integrated water-energy systems

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### Abstract

Sustainable development objectives surrounding water and energy systems are increasingly interdependent, and yet the associated performance metrics are often distinct. Regional planners tasked with designing future supply systems therefore require multi-criteria analysis methods and tools to determine a suitable combination of technologies and scale of investments. Previous research focused on optimizing system development strategy with respect to a single design objective, leading to potentially negative outcomes for other important sustainability metrics. This paper addresses this limitation, and presents a flexible and interactive multi-criteria model analysis framework and its application to long-term energy and freshwater supply planning at national or regional scales. The framework incorporates a linear systems-engineering model of the coupled supply technologies and inter-provincial electricity and water transmission networks. The multi-criteria analysis approach enables the interactive specification of diverse decision-making preferences for disparate criteria, and leads to learning on trade-offs between the resulting criteria values of the corresponding Pareto-optimal solutions. A case study of the water-stressed nation of Saudi Arabia explores preferences combining aspiration and reservation levels in terms of cost, water sustainability and CO<sub>2</sub> emissions. The analysis reveals a suite of trade-off solutions, in which potential integrated system configurations remain relatively ambitious from both an economic and environmental perspective. The identified cost savings would have a major impact on the affordability of water and electricity services in Saudi Arabia.

### Keywords:

Water-energy nexus; climate change mitigation; energy systems analysis; capacity expansion planning; Pareto-optimal solutions; Saudi Arabia

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## 1. Introduction

Water plays a key role in the supply of energy in many regions globally, primarily for thermal power plant cooling and hydropower generation [1]. Constraints on the availability of water resources in these regions therefore pose risks to energy service reliability. At the same time, a significant amount of energy is required to extract, treat and distribute freshwater resources [2]. Constraints on the supply of freshwater services therefore pose risks of additional energy requirements. Moreover, energy and freshwater are required for meeting the development goals of societies. These interdependencies are often referred to as the water-energy nexus, and promote integrated planning of water and energy infrastructure systems.

Infrastructure here refers to the technologies or processes that enable supply of energy and water services to consumers. Planners tasked with designing regional energy and freshwater infrastructures are faced with a plethora of technologies and a wide variety of economic, social and environmental conditions, which make it difficult to decide which technologies to invest in and promote, and in what order. The optimal combination of technologies and level of investments will be difficult to determine without appropriate analysis methods and tools. From this perspective, mathematical programming models have provided critical decision support by enabling planners to identify system designs that perform well under anticipated operational conditions [3–8].

Previous studies explored impacts of water constraints on energy system operation by coupling water supply and electricity generation dispatch models [9–13]. Several other previous studies note the importance of future capacity decisions (the size and location of technologies) in terms of enabling effective adaptation to future water constraints, and examined the impact of water availability on the development of regional power systems by adding explicit water constraints to an optimal infrastructure planning model [14–21]. Water constraints are found to primarily cause a shift towards water-efficient cooling technology for thermal power generation, as well as increased siting in regions with greater access to water availability [18]. Increased hydrologic variability under climate change was also found to cause further long-term capacity challenges in regions where hydropower plays an important role in electricity supply [15, 20]. A key limitation of these previous analyses of water constraints is the inability to incorporate feedbacks from future water supply development, which will impact the availability of water for energy and water-related energy demand. To reconcile development interdependencies, a number of other studies link freshwater and energy infrastructure planning models directly [22–29]. This approach enables modeling of system configurations that adapt to undesirable interactions between water and energy during infrastructure development.

Most previous coupled planning models focus on identifying system configurations that minimize costs or maximize consumer surplus. Yet, there are often other social or environmental objectives of concern to regional decision-makers and stakeholders, thus requiring a more integrated approach to assessing system performance [30]. Metrics of interest include limiting greenhouse gas emissions and air pollution, and securing food, water and energy resources. Previous analyses addressed such objectives as constraints, values of which were explored using parametric optimization [16, 27, 28, 31]. Parametrization of constraints requires not only skilled analysts but also specification of a large

35 number of optimization problems, many of which are either infeasible or result in dominated (inefficient) solutions.  
36 Multi-criteria analysis (MCA) of discrete alternatives can be applied to the results of parametric model optimization  
37 [31], but such a two-stage process is by far less effective than a direct linking of the model with the MCA tool. An-  
38 other popular approach is based on weighted-sum criteria aggregation into a composite goal function. This approach  
39 has, however, serious shortcomings [32], e.g.,: (1) in some situations the same solution is returned even if substantial  
40 changes are made to the weights; (2) many efficient solutions<sup>1</sup> cannot be obtained by varying the weights; and (3)  
41 increasing a weight does not guarantee improvement of the corresponding criterion value.

42 In this context, formal MCA methods offer an improvement to traditional optimization approaches, as illustrated  
43 by a sample of applications relevant to the case study presented in this paper [33–36]. MCA supports analysis of  
44 tradeoffs between all relevant objectives, and interactive exploration of diverse efficient solutions across multiple  
45 objectives. Despite the potential to apply this type of methodology and tools to effectively model coupled economic-  
46 environmental decision-making [37], application of MCA to the integrated planning of energy and water systems has  
47 been limited to cooling technology choices in the power sector [38].

48 This paper presents a novel systems analysis tool for integrated regional planning of energy and freshwater supply  
49 systems. The framework incorporates a multi-objective decision support system to enable analysis of long-term  
50 infrastructure strategies that balance economic, energy and water sustainability objectives. The integrated decision  
51 support framework is demonstrated within a case study of the water-stressed, carbon-intensive nation of Saudi Arabia.  
52 The results of the analysis provide important new insights into the following research questions:

- 53 • How can multiple design criteria be incorporated into long-term infrastructure planning models covering both  
54 the water and energy supply sectors?
- 55 • What is the potential scale of tradeoffs between environmental and economic development objectives in the case  
56 study region, and how might relaxing ambition levels for water and energy sustainability impact affordability?

57 The paper proceeds as follows. The methodology of model-based decision-support and its implementation for in-  
58 tegrated water-energy systems is presented in Section 2. The case study demonstrating model application is described  
59 in Section 3 followed by the discussion of results in Section 4. Conclusions from the research are summarized in  
60 Section 5.

## 61 **2. Methodology**

62 This section presents the approach for coupled water-energy supply planning and its integration with the MCA  
63 methods and tools. The framework is based around a water-energy infrastructure planning model developed previously  
64 for Saudi Arabia [28]. Previous research with this framework demonstrated that transitioning away from nonrenewable

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<sup>1</sup>Solutions are called efficient or Pareto-optimal if there exists no other solution for which at least one criterion can be made better without sacrificing performance of the criteria.

65 groundwater use by the year 2050 in Saudi Arabia could increase electricity demand by more than 40% relative to  
66 2010, due to rapid development of desalination and water conveyance infrastructure, and require investments similar  
67 to strategies aimed at transitioning away from fossil fuels in the electricity sector. These results highlight the need to  
68 incorporate multiple policy objectives into system design, and is the key feature of the enhanced MCA tool proposed  
69 in the current study. Following a description of the mathematical model for coupled water-energy supply planning, we  
70 discuss its integration with the applied MCA methodology. Finally, we describe the input data and scenarios explored  
71 in the case study demonstrating model application.

### 72 *2.1. A core model for integrated water-energy infrastructure development*

73 The planning challenge dealt with in this paper is the sustainable long-term development of water and energy  
74 systems. These decisions are typically made at national or regional-scales, and encompass choices surrounding the  
75 capacity of existing and future infrastructure. Capacity decisions are key design parameters for energy and water sup-  
76 ply planners due to the relationship with geographical constraints, investment costs and long-term structural inertia of  
77 the supply systems [4]. Capacity choices incorporate both the size and location of new technologies, as well as the  
78 operational management (activity) of the technologies over the planning horizon. Strategizing capacity decisions is  
79 also commonly referred to as capacity expansion planning, but may also entail reductions in system capacity in situa-  
80 tions where reduced demands are projected. Due to the impact on long-term structural inertia, capacity decisions are  
81 usually assessed over multi-decadal time periods. Performance criteria of primary concern include service reliability,  
82 end-use prices and environmental impacts.

83 Water and energy resource potentials represent an important input to any capacity planning approach, and vary  
84 significantly across resources, time and geographic location. Transporting water and energy from one location to  
85 another also requires massive investment in network infrastructure, with long-distance water conveyance presenting  
86 further interdependencies due to the energy required for pumping. Planning models incorporating spatially resolved  
87 infrastructure systems will be needed to understand the implications of local constraints and transmission for long-  
88 term development strategy [24, 39–42]. Yet, there is also a need to maintain an adequate temporal resolution in order  
89 to capture operational constraints occurring primarily in the electricity sector [43]. Moreover, spatial units typical  
90 in water resource management are geophysically-based and do not necessarily align with administrative units typical  
91 in energy supply planning (e.g., national, provincial, utility, etc.). The spatial mismatch may require disaggregation  
92 of spatial decision-making units in order to converge on a common resolution across energy and water systems [44].  
93 The added complexity will be additionally demanding to accommodate in mathematical models containing an already  
94 diverse range of technologies and processes. Maintaining a careful balance between spatial and temporal scales  
95 when developing integrated water-energy models for long-term planning purposes is thus a critical challenge for  
96 regional planners, and scoping will depend on the specific research question (e.g., transmission expansion, emissions  
97 mitigation, groundwater depletion, etc.) and characteristics of the study region (interconnectivity of basins/aquifers,  
98 population density, income-level, etc.).

99 In this paper, we adapt the Saudi Arabia Electricity-Water Planning model (SEWP): an integrated supply planning  
100 framework that incorporates simultaneous capacity decisions in the water and electric power sectors. The framework  
101 includes a diverse range of technologies including most power generation types (e.g., natural gas combined-cycle,  
102 concentrating solar power, etc.) and water supply technologies (e.g., groundwater extraction, desalination, wastewater  
103 recycling, etc.). Thermal power plants are further distinguished by cooling technology (e.g., once-through, recircu-  
104 lating, etc.). The study region is broken into the 13 provincial administrative regions, with expandable electricity and  
105 freshwater transmission between provinces included in the capacity planning decisions. To explore impacts of na-  
106 tional policy and path-dependency on technology deployment, SEWP focuses on a planning horizon of 2010 to 2050  
107 in 5-year segments, with each time-step solved concurrently. Each modeled year is broken into monthly timeslices  
108 to enable treatment of seasonal effects, such as the potential mismatch between available supply and demand. For  
109 computational efficiency, the current version of SEWP considers linear relationships between variables. Although  
110 designed specifically for application to infrastructure planning in Saudi Arabia, the approach is readily adaptable to  
111 other regional situations.

112 SEWP ensures a physical representation of resource conversion across a set of  $R$  resources,  $I$  spatially distributed  
113 regions, and  $T$  temporally distributed decision making intervals. For each resource  $r \in R$ , location  $i \in I$  and time-step  
114  $t \in T$ , the managed supply must exceed the exogenous demand:

$$Q(r, i, t) + \Delta S(r, i, t) \geq D(r, i, t) \quad (1)$$

115 where  $Q$  is the managed flow from supply technologies,  $\Delta S$  is the managed flow from storage, and  $D$  is the exogenous  
116 demand. The managed flow from supply technologies includes consumption and production of different energy and  
117 water resources at the technology-level, and can be modeled consistently using appropriate functional relationships  
118 that link technology activity to net resource availability. SEWP considers a diverse set of  $P$  technologies capable  
119 of operating in a set of  $O$  operational modes, and calculates the managed flow of resource  $r \in R$  from a specific  
120 technology  $p \in P$  using input activity ratios  $\epsilon^{in}$  and output activity ratios  $\epsilon^{out}$ . The activity ratios represent the average  
121 rate at which a certain technology consumes or produces a certain resource per unit of activity-level. Operational  
122 modes are distinguished to enable representation of diverse operating costs and efficiencies for a single technology  
123 type. To allow for spatial transfers of water and electricity via conveyance or transmission infrastructure, net resource  
124 flows in each region  $i \in I$  incorporates inputs produced and consumed in that region, as well as from other regions  
125  $j \in I$ . Summing across regions, modes and technologies yields the managed flow for each resource in each region and  
126 time step:

$$Q(r, i, t) = \sum_{p,o,j} \left[ \epsilon^{out}(r, p, o, j, i, t) \cdot x(p, o, j, t) - \epsilon^{in}(r, p, o, i, j, t) \cdot x(p, o, i, t) \right] \quad (2)$$

127 where  $x$  is the activity-level of a specific technology. The change in storage-level is equivalent to the difference

128 between the levels across decision-making intervals:

$$\Delta S(r, i, t) = s(r, i, t) - s(r, i, t + 1) \quad (3)$$

129 where  $s$  is the storage-level. Surface water reservoirs and potable storage at end-use are the only between-month  
 130 storage technologies currently included in SEWP. Level-dependent losses are important for surface water reservoirs  
 131 (evaporation is proportional to surface area), and can be accounted for using linearized area-volume relationships  
 132 [45]. Saudi Arabia contains relatively little exploitable surface water and associated storage, and for this reason,  
 133 volume-dependent losses are neglected. Due to uncertainties surrounding the scale of the resource and complexities  
 134 of hydro-geological modeling, groundwater storage is incorporated into SEWP as a model criteria (section 2.2).

135 The activity-level of each technology is constrained in SEWP by the available capacity:

$$\phi(p, i, t) \cdot z(p, i, t) - \sum_o \sigma(p, o, i, t) \cdot x(p, o, i, t) \geq 0 \quad (4)$$

136 where  $z$  is the installed capacity,  $\phi$  is the fraction of installed capacity that is available (or the capacity factor), and  $\sigma$   
 137 is the rate at which a particular operational mode utilizes capacity. Certain operational modes are allowed to consume  
 138 more capacity than others in the model to reflect e.g., capacity impacts of scheduling flexible reserve generation in the  
 139 electricity sector [46]. SEWP includes incremental capacity expansion decisions  $u$  that alleviate capacity constraints.  
 140 Incremental capacity retirements  $w$  are also modeled as decision variables to allow representation of finite technology  
 141 lifecycles. The installed capacity of a particular technology is given by:

$$z(p, i, t) - z(p, i, t + 1) + u(p, i, t) - w(p, i, t) = 0 \quad (5)$$

142 Likewise, storage capacity  $c$  constrains storage levels, incremental new storage capacity  $b$  can be used to alleviate  
 143 constraints on storage levels, and incremental storage retirements  $d$  reduce installed storage capacity:

$$\psi(r, i, t) \cdot c(r, i, t) - s(r, i, t) \geq 0 \quad (6)$$

144

$$c(r, i, t) - c(r, i, t + 1) + b(r, i, t) - d(r, i, t) = 0 \quad (7)$$

145 where  $\psi$  is the fraction of installed storage capacity that is active. In the case reported in this paper, capacities are  
 146 modeled by continuous variables. The authors are aware that integer variables enable modeling the effects of reduced  
 147 unit costs with increasing unit size (i.e., economies-of-scale), which provides insight into the benefits of distributed or  
 148 centralized supply configurations [26, 40]. However, the choice of continuous variables is justified by two arguments.  
 149 First, the obtained capacity values usually provide a good approximation. Second, and most importantly, due to the  
 150 model size its mixed-integer formulation would require qualitatively more computational resources.

151 Upper and lower bounds are further imposed on the capacity and activity variables to reflect e.g., resource avail-  
 152 ability, excess supply and existing infrastructure. Other additional constraints address operational policies such as  
 153 technology retirements, inter-annual reservoir sustainability and electricity system flexibility. A detailed account of  
 154 these relationships can be found elsewhere [28], and for brevity are not repeated here.

## 155 2.2. Multi-criteria model analysis

156 A vector of outcome variables  $\mathbf{y}$  can be used for measuring various consequences of the simulated development  
 157 strategy in SEWP. Outcome variables are often named differently (e.g. criteria, objectives, goals, metrics, performance  
 158 indices, etc.). A vector of algebraic relations  $\mathbf{F}$  are defined that convert decisions variables to outcomes:

$$\mathbf{y} = \mathbf{F}(\mathbf{v}) , \mathbf{v} \in V_o \quad (8)$$

159 where  $\mathbf{v}$  is the vector of model decision-variables (the activity and capacity of the technologies introduced in the pre-  
 160 vious section), and  $V_0$  is the set of feasible solutions (admissible due to the physical and logical constraints introduced  
 161 in the previous section).

162 Past application of SEWP focused on a single objective: minimize total discounted system costs over the planning  
 163 horizon. This formulation requires a unique specification of a goal function that adequately represents system cost.  
 164 Capital and operational cost parameters for each technology are input to SEWP and multiplied by the corresponding  
 165 capacity or activity variable to estimate the cost contribution. Discounting is then used to translate future costs  
 166 into an estimated present value. In the single-objective formulation, preferences for outcomes, including available  
 167 budget, requires a re-definition of the set of feasible solutions  $V_0$  by  $V_1$ :  $V_1 = V_0 \cap \mathbf{P}$ , where  $\mathbf{P}$  is the set of outcomes  
 168 conforming to the decision-making preferences. In some cases the preferences are too ambitious, e.g., tight constraints  
 169 on the budget actually shrinks the set of feasible solutions to a small subset (which ignores many possibly interesting  
 170 solutions), or even results in an empty set  $V_1$ , which in turn makes the underlying optimization problem infeasible.

171 Alternatively, preferences for multiple objectives might be obtained based on linear weighted-sum criteria aggre-  
 172 gation into a composite goal function. This approach has the serious shortcomings mentioned in the introductory  
 173 section [32]. In this paper, an achievement scalarizing function (ASF) serves as the goal function in the mathematical  
 174 programming analysis built on the core model described in the previous section. The ASF is defined through crite-  
 175 ria achievement functions (CAFs) specified for each objective independently. The role of the CAFs is to provide a  
 176 common measure for criteria performance, typically defined in different metrics and scales. We utilize a modified  
 177 version of the reference point methodology [37, 47], where each CAF is parametrized by two values specified by the  
 178 user, namely aspiration and reservation levels, which correspond to the criterion values that are desired and worst  
 179 acceptable, respectively. In this context, a CAF for the  $k$ -th criterion is denoted by:

$$u_k = f_k(q_k, \bar{q}_k, q_k^*), \quad (9)$$



180 where  $f_k(\cdot)$  is a strictly monotone concave function (decreasing for minimized, and increasing for maximized criteria,  
181 respectively), and  $q_k, \bar{q}_k, \underline{q}_k$  are the criterion value, aspiration, and reservation levels, respectively. Values of  $q_k$  are de-  
182 fined by the corresponding outcome variables of the analyzed core model (i.e.,  $q_k = y_k$ ). The  $f_k(\cdot)$  are usually defined  
183 as piece-wise linear functions with linear segments determined by the utopia, aspiration, reservation, and nadir values  
184 [48]. The utopia point  $\mathbf{U}$  is defined by a vector composed of the best values of all considered criteria. Utopia com-  
185 ponents are easily computed through the so-called *selfish* optimizations (i.e., optimizing each criterion separately).  
186 The nadir point  $\mathbf{N}$  is defined by the worst values of the criteria within the Pareto-set. The piece-wise linear functions  
187 represent the human values related to satisfaction and regret, and also have a nice mathematical property; namely, the  
188 underlying multi-criteria optimization model remains linear for linear core models. A correctly implemented multi-  
189 criteria model analysis framework does not impose any restrictions on the feasibility of the aspiration and reservation  
190 values, other than two exceptions: (1) the reservation is lower/higher than aspiration for minimized/maximized cri-  
191 terion, respectively; and (2) the aspiration and reservation values are between the corresponding utopia and nadir  
192 values.

193 The CAF values have a very easy and intuitive interpretation in terms of the degree of satisfaction from the  
194 corresponding value of the criterion. Values of 1 and 0 indicate that the value of the criterion exactly meets the  
195 aspiration and reservation values, respectively. CAF values between 0 and 1 can be interpreted as the degree of  
196 satisfaction of the criterion value, i.e., to what extent this value is close to the aspiration level and far away from  
197 the reservation level. These interpretations correspond to the interpretation of the membership function from fuzzy  
198 set theory [48]. In fact, the CAF extends the membership function concept because the CAF also takes negative  
199 values (for criteria values worse than the reservation), and values greater than one (for criteria values better than the  
200 aspiration). This extension is necessary for proper handling of any  $\bar{q}_k$  and  $\underline{q}_k$ , which in turn frees the users from  
201 concerns regarding attainability of the considered aspiration and reservation levels.

202 The ASF is defined by:

$$\mathcal{S} = \min_{k \in K_a} (u_k) + \frac{\epsilon}{K} \cdot \sum_{k=1}^K u_k \quad (10)$$

203 where  $K_a$  is the subset of active criteria,  $u_k$  are defined by (9), and  $\epsilon$  is a small positive number. The first term causes  
204 improvement of the worst performing (in terms of the corresponding CAF) criterion. The second term assures that the  
205 optimal solution provided for maximization of the ASF is indeed Pareto-optimal [37, 49]. Maximization of (10) for  
206  $\mathbf{v} \in V_o$  generates a properly efficient solution aligned with the user's criteria preferences.

207 Implementation of the MCA methods described in this paper is accomplished with the Integrated Modeling En-  
208 vironment Project's online Multiple Criteria Model Analysis (MCMA) framework [50]. The approach is outlined in  
209 Appendix A.

### 210 3. Case study

211 The focus of the Saudi Arabia case study analysis are infrastructure strategies that are efficient at simultaneously  
212 minimizing investment costs, groundwater extraction and carbon dioxide (CO<sub>2</sub>) emissions. These objectives are  
213 selected as the focus for the analysis due to the anticipated challenges in balancing future socioeconomic development  
214 with aspirations surrounding global climate stewardship and national food security. The former is a concern due to  
215 increasingly stringent global climate change policy, and the fact that more than half of the current power generation  
216 fleet in Saudi Arabia burns extremely carbon-intensive crude oil [51]. Fulfilling national food security ambitions  
217 locally in Saudi Arabia's harsh desert environment requires industrial-scale irrigation, and has driven widespread  
218 over-exploitation of regional groundwater resources, leading to concerns regarding long-term supply sustainability  
219 [52]. Cost, emissions and groundwater criteria are accounted for in the SEWP model by tracking the corresponding  
220 cumulative value over the planning horizon (2010-2050) and over all sub-national regions (13 provinces).

221 The case study in this paper demonstrates the analytical efficiency of a multi-objective framing to long-term  
222 planning models of water and energy supply systems, and is applied within a scenario analysis involving interactive  
223 specification of the criteria aspiration and reservation levels. Relative levels of ambition across the disparate objec-  
224 tives are defined by normalizing the range between the nadir and utopia values for each criteria, and separating the  
225 normalized values into three intervals: *Ambitious* (+++), *Moderate* (++) , and *Relaxed* (+). The *Ambitious* criteria  
226 interval has the aspiration and reservation levels near the utopia point, whereas the *Relaxed* interval converges on the  
227 nadir. Scenarios involving a combination of these aspiration and reservation categories are initially defined to explore  
228 trade-offs between sustainability objectives. Following the initial assessment, a sensitivity analysis is performed in  
229 which approximately 100 model iterations are explored (i.e., criteria preferences specified by diverse combinations of  
230 the aspiration and reservation levels).

231 Technology performance and demands for electricity and water occurring in the agricultural, municipal and man-  
232 ufacturing sectors are key inputs to the MCA framework. The analysis in this paper focuses on a single technology  
233 performance scenario; sensitivity of the SEWP model to these assumptions were explored previously [28]. Exogenous  
234 demands from each sector are generated with quantitative socioeconomic projections that follow the Shared Socioe-  
235 conomic Pathways (SSP) [53]. National population and per capita GDP increase more than two-fold by 2050 in the  
236 mid-range (SSP2) scenario [54–56]. Previously derived sector-specific econometric models linking population and  
237 GDP to freshwater and electricity demand are used to convert the SSP data into provincial demand trajectories [28].  
238 Moderate levels of end-use technological change are included, and reflect expected efficiency improvements driven  
239 by technological innovation. The SSP2 scenario results in modeled national electricity demands (other than for water  
240 supply) increasing from approximately 200 TWh in 2010 to more than 700 TWh in 2050. Freshwater demands (other  
241 than for power supply) increase less dramatically, from 21 km<sup>3</sup> in 2010 to 25 km<sup>3</sup> in 2050, due to anticipated impacts  
242 of existing national agricultural policy [57]. A detailed account of the input data used to parameterize the model,  
243 including an assessment of existing infrastructure, can be found in [28].

244 **4. Results**

245 *4.1. Impact of multiple criteria on system cost*

246 This section presents key results of the scenario analysis with specific focus on the impacts of the MCA en-  
 247 hancements on system cost in the SEWP model. To highlight system boundaries, the scenario analysis initially  
 248 involves exploration of the utopia solutions, and then moves to adjusting the aspiration and reservation levels to ex-  
 249 plore compromise solutions. Outcomes for each criteria for a select range of aspiration and reservation levels obtained  
 250 through interactive scenario analysis are presented in Table 1. The relationship between the criteria for the selected  
 251 scenarios are also plotted in Figure 1, where results are indexed to the respective criteria outcome obtained in the  
 cost-minimization solution.

Scenario name	Criteria ambition-level			Criteria reservation ( $\underline{q}$ ), aspiration ( $\bar{q}$ ) and outcome ( $q$ )								
				Cost [ $\times 10^{12}$ USD ]			CO <sub>2</sub> [ $\times 10^9$ metric tons ]			GW [ $\times 10^3$ km <sup>3</sup> ]		
	Cost	CO <sub>2</sub>	GW	$\underline{q}$	$\bar{q}$	$q$	$\underline{q}$	$\bar{q}$	$q$	$\underline{q}$	$\bar{q}$	$q$
Cost selfish	(+++)	(-)	(-)	1.04	0.24	0.24	-	-	8.32	-	-	1.26
CO <sub>2</sub> selfish	(-)	(+++)	(-)	-	-	1.25	3.51	0.46	0.46	-	-	0.21
GW selfish	(-)	(-)	(+++)	-	-	2.17	-	-	4.04	0.39	0.03	0.03
GW-CO <sub>2</sub> ambitious	(+)	(+++)	(+++)	2.05	0.24	0.81	2.75	0.46	1.18	0.30	0.03	0.12
Cost-CO <sub>2</sub> ambitious	(+++)	(+++)	(+)	0.84	0.24	0.53	2.66	0.46	1.52	0.84	0.03	0.42
Cost-GW ambitious	(+++)	(+)	(+++)	0.84	0.24	0.56	7.31	0.46	4.07	0.30	0.03	0.17
CO <sub>2</sub> ambitious	(++)	(+++)	(++)	2.05	0.24	0.69	2.75	0.46	1.04	0.84	0.03	0.23
GW ambitious	(++)	(++)	(+++)	2.05	0.24	0.74	7.31	0.46	2.37	0.30	0.03	0.11
Cost ambitious	(+++)	(++)	(++)	0.84	0.24	0.47	7.31	0.46	3.04	0.95	0.03	0.38
Cost-GW-CO <sub>2</sub>	(+++)	(+)	(++)	0.84	0.24	0.50	7.31	0.46	3.40	0.64	0.03	0.29
Cost-CO <sub>2</sub> -GW	(+++)	(++)	(+)	0.84	0.24	0.49	5.03	0.46	2.32	0.95	0.03	0.41
All criteria ambitious	(+++)	(+++)	(+++)	0.48	0.24	0.62	1.38	0.46	1.89	0.15	0.03	0.22

Table 1: Parameterization of the decision-making preferences (aspiration and reservation levels) and the corresponding MCA results for the preliminary scenarios investigated. Each scenario is identified based on its level of ambition with respect to cost, CO<sub>2</sub> and groundwater (GW) objectives. Relative levels of ambition across the disparate objectives are defined by normalizing the range between the nadir and utopia values for each criteria, and separating the normalized values into three intervals: *Ambitious* (+++), *Moderate* (++) and *Relaxed* (+); *inactive* criteria are marked by (-). The *Ambitious* criteria interval has the aspiration and reservation levels near the utopia values, whereas the *Relaxed* interval converges on the nadir.

252

253 We find largest cost trade-offs in this preliminary analysis for the groundwater selfish scenario. Under the pa-  
 254 rameterized technology costs, this scenario represents a discounted system cost that is more than 8 times the cost-  
 255 minimization (cost selfish) solution. In fact, the cost selfish solution corresponds to the groundwater nadir outcome,  
 256 highlighting the direct trade-offs between these objectives. The CO<sub>2</sub> selfish solution is also more than 6 times expen-  
 257 sive than the cost-minimization solution; however, this scenario also achieves groundwater co-benefits, as indicated by  
 258 the 80% drop in cumulative groundwater extraction compared to the cost-minimization solution (Figure 1). Varying  
 259 the criteria aspiration and reservation levels across the other scenarios listed in Table 1 reveals that the largest costs  
 260 are incurred when fulfilling the stringent CO<sub>2</sub> and groundwater preferences, and that a slightly relaxed criteria prefer-  
 261 ence can achieve significant cost savings while remaining ambitious from an environmental perspective. For example,  
 262 when all criteria are set to relatively ambitious preferences (i.e., the 'all criteria ambitious' scenario), the MCA model

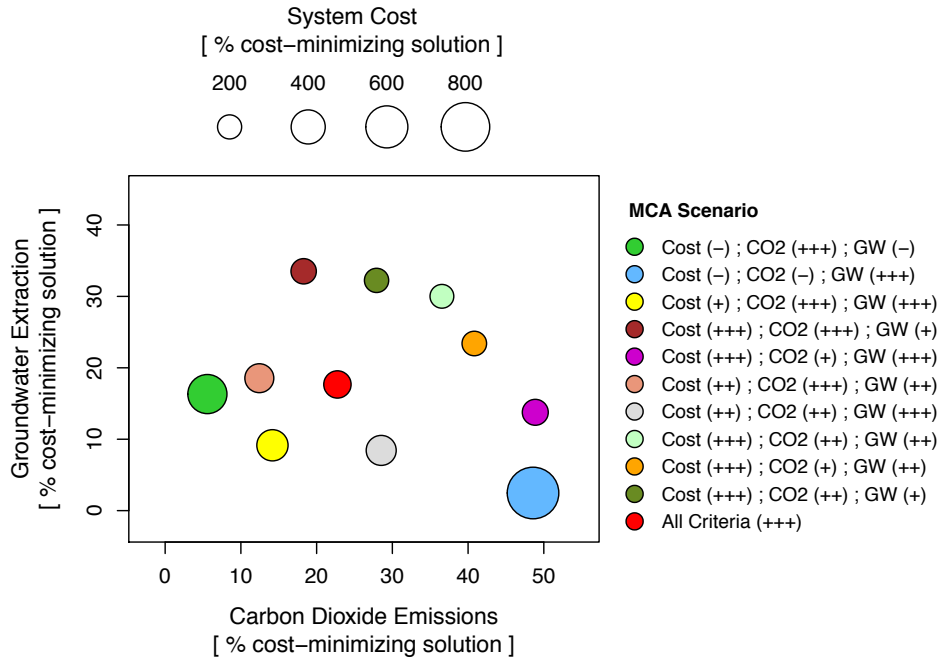


Figure 1: Investment cost, groundwater extraction and CO<sub>2</sub> emission outcomes obtained for the scenarios listed in Table 1. The marker area is proportional to the discounted system cost. Results are indexed to the respective criteria outcome obtained in the cost-minimization solution.

263 seeks a Pareto-optimal solution that is relatively balanced across objectives. Pareto-optimal in this context refers to  
 264 a solution where there exists no other solution for which one of the criterion (i.e., discounted costs, CO<sub>2</sub> emissions  
 265 and groundwater extraction) can be made better without sacrificing performance of the other criteria. The discounted  
 266 system cost in this solution is only 2.5 times the cost-minimization outcome, but simultaneously achieves deep reductions  
 267 in cumulative groundwater extraction (more than 80% reduction versus the cost-minimization outcome) and  
 268 cumulative CO<sub>2</sub> emissions (more than 75% reduction versus the cost-minimization outcome). Further relaxing the  
 269 cost preferences (i.e., the 'GW-CO<sub>2</sub> ambitious' scenario) results in a system that is 3.4 times more expensive than  
 270 the cost-minimization solution, but achieves a further 10% reduction in cumulative groundwater extraction and CO<sub>2</sub>  
 271 emissions. The level of mitigation in this latter scenario is likely required to avoid local groundwater shortages [58],  
 272 and achieve national electricity sector contributions to global climate stabilization [59].

#### 273 4.2. Impact of criteria preferences on system configuration

274 Impacts of the criteria settings on the provincial-level technology build-out for selected scenarios are provided in  
 275 Figure 2. Depicted is the optimal annual electricity and freshwater supply mix in each region, as well as the inter-  
 276 provincial transfers and demand-levels. The cost-minimization solution (Figure 2a) involves expansion of relatively  
 277 low-cost combined-cycle natural gas generation, with existing renewable energy policy driving development of 50  
 278 GW of mostly solar generation capacity. Groundwater withdrawals are left unconstrained in the cost-minimization

279 model, and under the parameterized costs dominate the future water supply mix and displace existing interprovincial  
280 desalination transfers. Moreover, in the cost-minimization solution thermal power plants employ once-through fresh-  
281 water cooling systems due to the low investment cost and lack of concern surrounding groundwater sustainability.  
282 The modeled extraction across sectors in this scenario likely exceeds available aquifer storage [58].

283 In the groundwater selfish solution (Figure 2b) costs are more than 8 times the cost-minimization solution due  
284 to the rapid expansion of desalination, wastewater recycling and rainwater harvesting, and corresponding develop-  
285 ment of highly integrated interprovincial conveyance networks to meet water demands located inland. The increased  
286 electricity load from the water sector technologies increases aggregate national electricity demand in 2050 by 12%  
287 compared to the cost-minimization solution, and additional electricity sector capacity is developed to meet these re-  
288 quirements. Deep reductions in technology costs projected later in the simulation horizon combined with a lack of  
289 water requirements results in solar PV dominating the 2050 electricity supply mix in the groundwater selfish solution,  
290 and large-scale investment into electricity storage and load control capacity enables this transition (not depicted).

291 Similar characteristics of the 2050 supply mix are apparent when all criteria are set to ambitious preferences  
292 (Figure 2c). The push to reduce costs in this scenario results in a slower transition away from groundwater extraction  
293 and CO<sub>2</sub> emissions, and enables groundwater and fossil fuel generation to continue to provide services in areas  
294 facing costly infrastructure constraints. For example, inland provinces continue to extract groundwater in the 'all  
295 criteria ambitious' scenario to displace investment in rainwater harvesting and conveyance infrastructure, and fossil  
296 fueled power plants are operated to provide flexibility to displace investment in storage technology and transmission  
297 upgrades.

### 298 4.3. Sensitivity analysis

299 The sensitivity analysis involved over 100 model iterations (i.e., preferences specified by diverse combinations  
300 of the aspiration and reservation levels). Each of the identified Pareto-optimal solutions has a certain trade-off (com-  
301 promise) between criteria values. However, in decision-making practice extreme solutions (i.e., solutions with very  
302 good values for some criteria and very bad for the other criteria) are rarely accepted. As an example of exploration of  
303 criteria trade-offs we examine the iterations presented in Figure 3. The solutions are sorted by increasing cost.

304 Similar to the preliminary analysis, solutions with low cost have very high levels of CO<sub>2</sub> emissions and ground-  
305 water extraction. For a relatively small increase of cost one can achieve substantial reduction to the other two criteria,  
306 although such reductions are not monotone for both criteria. On the other hand, solutions with very low levels of  
307 CO<sub>2</sub> and groundwater are very expensive. This illustration of various efficient solutions provides a good basis for  
308 selecting a subset of the Pareto-frontier for further exploration. Such a selection depends on the preferences of actual  
309 decision-makers.

310 In a real-world planning scenario, the results of the sensitivity analysis can be presented to decision-makers who  
311 decide on the actual available budget and the goals for the other criteria. The primary role of the MCA is to help  
312 these decision-makers identify goals for all criteria that are simultaneously attainable. The MCA scenarios aligned

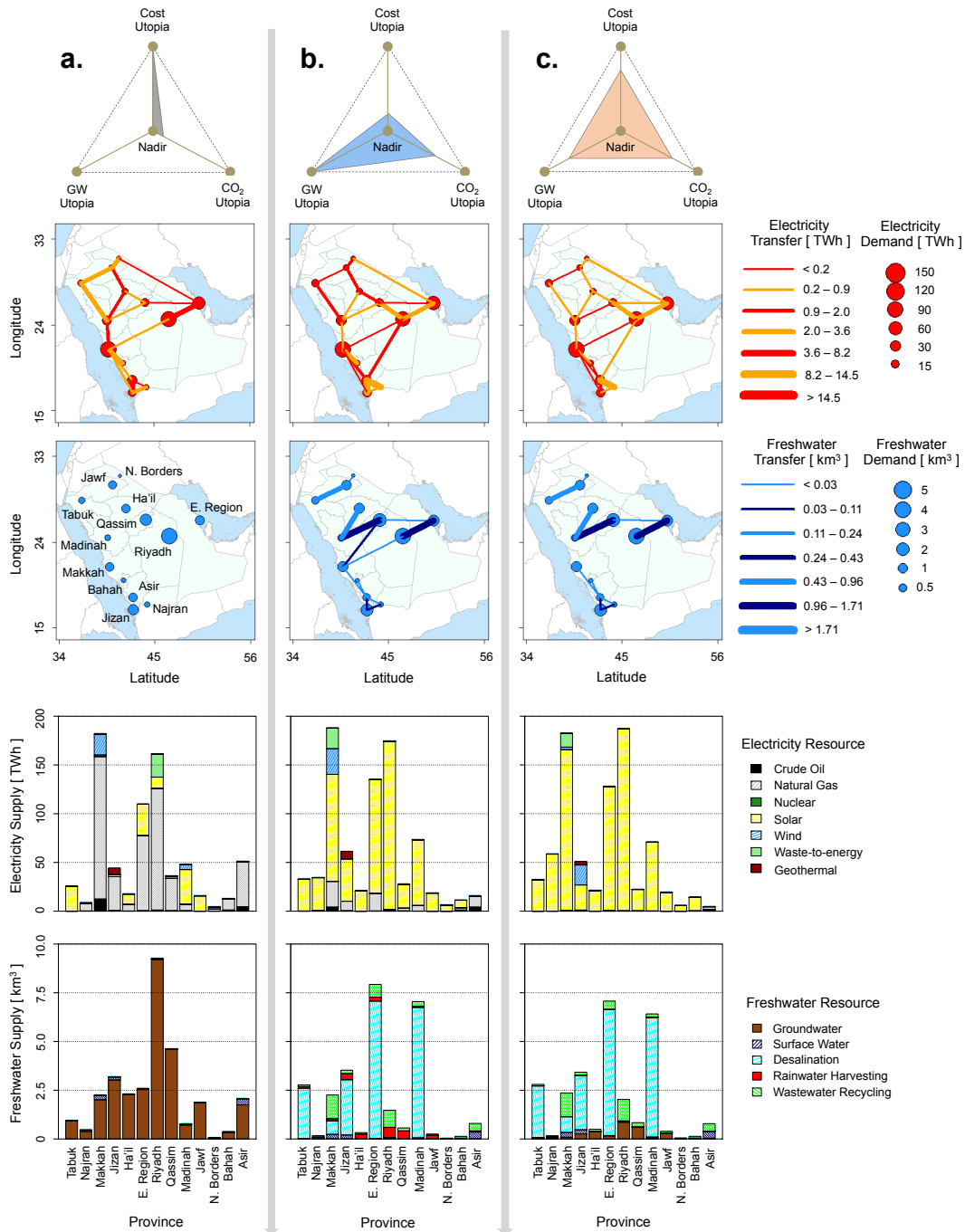


Figure 2: Provincial electricity and freshwater supply in 2050 for three of the MCA scenarios listed in Table 1. a. Cost selfsh (minimization) solution; b. Groundwater (GW) selfsh solution; c. All criteria ambitious solution. The top row depicts the criteria outcomes in relation to the Utopia and Nadir points. Row two and three from the top depict the annual freshwater and electricity transfers between provinces, as well as the scale of annual demand. The bottom two rows depict the supply mix from the different resources.

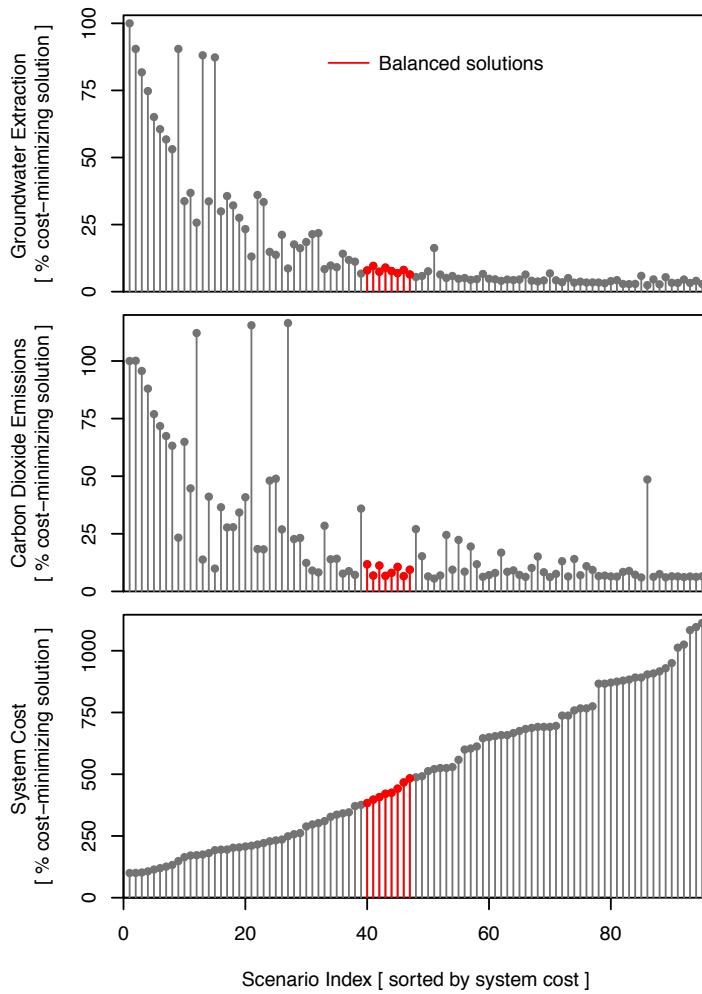


Figure 3: Criteria outcomes for the extended scenario analysis and identification of potential balanced solutions. Results are indexed to the respective criteria outcome obtained in the cost-minimization solution.

313 with the decision-makers' preferences would then be further vetted with detailed operational analysis and stakeholder  
314 involvement [60].

315 For example, solutions in the region marked as *balanced solutions* in Figure 3 might be considered as having good  
316 compromises between the criteria values, as each of them achieves relatively ambitious outcomes for both groundwater  
317 and CO<sub>2</sub> with relatively moderate impact on costs. Mitigation costs increase rapidly for more expensive solutions with  
318 relatively little improvement over the other criteria, and can therefore be deemed cost-prohibitive. Balanced solutions  
319 display similar system configurations in 2050 as in (Figure 2c), but are distinct with respect to implementation time.  
320 Largest cost savings are found to accompany balanced solutions that wait longest to transition away from groundwater.

## 321 **5. Conclusion**

322 Water and energy systems are increasingly interdependent, and will benefit from integrated long-term development  
323 strategy. Diverse performance criteria across development objectives necessitate multi-criteria assessment methods  
324 and tools. This paper presented a multi-criteria model analysis framework for long-term energy and water supply  
325 planning at national or regional scales. The framework incorporates a linear systems-engineering model of the coupled  
326 supply technologies and intra-regional transmission networks. A modified version of the reference point methodology  
327 enables interactive specification of decision-making preferences for disparate sustainability criteria, and convergence  
328 on a Pareto-optimal solution reflecting the relative criteria ambition-levels. Scenarios involving a combination of  
329 economic, climate and groundwater sustainability preferences were explored in the context of national planning in  
330 Saudi Arabia to demonstrate the performance of the novel analysis framework, as well as to quantify criteria trade-  
331 offs specific to the case study region.

332 Application of the integrated modeling framework in the case study region demonstrates important tradeoffs be-  
333 tween diverse sustainability criteria. Similar to previous research [28], we find that policy objectives in Saudi Arabia  
334 for 2050 that reduce cumulative groundwater extraction and electricity sector CO<sub>2</sub> emissions to levels likely needed  
335 to avoid local groundwater shortages and meet global climate stabilization targets are associated with a significant  
336 increase in system investment costs. However, the MCA framework in this paper goes further by revealing a suite  
337 of trade-off solutions that remain nearly ambitious at much lower costs. These savings would impact the affordabil-  
338 ity of water and energy services in the rapidly developing nation of Saudi Arabia. This result is relevant from a  
339 policy-perspective because it underscores the importance of identifying a suitable compromise between sustainability  
340 objectives during the formulation of long-term water and energy strategy.

341 Our results further demonstrate that a conventional linear systems-engineering model used to identify optimal  
342 capacity expansion policies and investment strategies for integrated water-energy systems can be efficiently converted  
343 into a multi-objective framework using a generic transformation algorithm. Overall, the MCA framing is found to  
344 require approximately the same computational effort to solve each scenario as the single-objective framing, with the  
345 added benefits of significant analytical efficiency in terms of long-term performance assessment due to the capabilities



346 in balancing multiple development objectives. It is therefore recommended that regional policy-makers incorporate  
347 similar MCA methods into their assessment of long-term water and energy strategy.

348 The scope of model applications in this paper focuses mainly on the electricity sector. Future work should consider  
349 expanding the system boundaries to allow assessment from resource extraction through to end-use services. This  
350 would allow mapping the impacts from a more comprehensive set of technologies and demand management policies  
351 to energy and water sustainability metrics of interest. An important issue to address in this context is the linking  
352 of surface and groundwater management, which was simplified in the analysis due to surface water scarcity in the  
353 case study region. Moreover, the effects of other criteria important to regional planners (e.g., air pollution, energy  
354 security, investment risk, climate change impacts, etc.) on the optimal development strategy should be explored to  
355 fully highlight potential trade-offs or synergies. The general MCA framework proposed in this paper can readily be  
356 adapted to include these features, and will be the topic of future research.

## 357 **Appendix A. MCA process and implementation**

358 This supplementary material describes in greater detail the MCA procedure applied in this paper and its imple-  
359 mentation as an integrated software tool. This framework is embedded in the modular web-based tool for multiple  
360 criteria model analysis (MCMA) [50].

### 361 *Appendix A.1. Process*

362 Specification of the MCA starts with uploading the core model provided either in the standard mathematical  
363 programming system (MPS) format or as a General Algebraic Modeling System (GAMS) format model. In this  
364 paper, the core model is written in the GNU mathematical programming language and converted to MPS format. The  
365 names of the core model variables are presented to the user, who selects those to be used as criteria, and defines the  
366 corresponding criterion name and type (either minimization or maximization). The uploaded core model together with  
367 the criteria specification constitutes the MCA problem instance, definition of which triggers a set of optimization tasks  
368 necessary for computing the pay-off table, i.e., the values of utopia components and an approximation of the nadir.  
369 Computation of the pay-off table requires  $4 \cdot K$  optimizations, where  $K$  is the number of selected criteria. After these  
370 computations are completed, the MCA problem instance is ready for interactive analysis. An option for defining more  
371 than one analysis instance is used in diverse situations, e.g., when problems are analyzed by several users or if a user  
372 wants to make several analyses each with a different focus. The initial analysis instance is generated automatically.  
373 Subsequent instances are optionally created by the users whenever desired.

374 MCA is an iterative process supporting the user in the Pareto set exploration that aims at finding subsets of solu-  
375 tions with desired properties (e.g., cheap, or moderately priced, or expensive). Therefore each analysis is composed  
376 of iterations. To provide an initial view on the Pareto-set, several iterations are generated automatically. First, efficient

377 solutions corresponding to each utopia component are generated by selfish optimization of the corresponding crite-  
378 rion, i.e., all other criteria are set to be inactive. Finally, an example of balanced preferences is generated by setting  
379 for each criterion the same relative (to the utopia/nadir range) levels of aspiration and reservation.

380 With the above summarized background information the user takes full control of further iterations. For each iter-  
381 ation the user analyzes the Pareto-solutions obtained in previous iterations, and considers which criteria he/she wants  
382 to improve and which should be compromised, and then sets values for each criterion of aspiration and reservation  
383 aiming at obtaining an efficient solution that fits their preferences (desired trade-offs between criteria values) better.  
384 At each iteration the multi-criteria problem is converted into an auxiliary parametric single-objective problem using  
385 the achievement scalarizing function given by (10), the solution of which provides a Pareto solution hopefully having  
386 a better trade-off between criteria than the previous solution.

387 Typically, the MCA users explore various areas of the Pareto frontier (e.g., cheap and expensive having the cor-  
388 responding bad and good values of environmental criteria) before deciding which compromises between the criteria  
389 values fit best their preferences. Examples of this process are provided in Section 4, and more methodological back-  
390 ground in [32, 37, 48, 49].

#### 391 *Appendix A.2. Implementation*

392 The MCA of the model described in Section 2.2 was done with the MCMA, modular web-based tool for multiple  
393 criteria model analysis [50]. The MCMA tool implements the methodology described in Section 2.2 and enables anal-  
394 ysis of models provided in either the standard MPS format for linear programming (LP) models or models specified in  
395 GAMS. In order to enable a proper MCA the core models should conform to specific requirements on the core model  
396 (i.e., outcome variables defined, no constraints due to preferences, optimization criterion ignored, etc.).

397 The workflow of the MCA implementation is actually hidden from the MCA users, who are guided through the  
398 MCA process (described in Appendix A.1) by a typical Graphical User Interface (GUI). The SEWP core model  
399 described in Section 3 is initially generated in the standard MPS format in the same way as for the traditional single-  
400 criterion optimization; only the constraints for objectives other than cost are not generated. Then the MCMA tool  
401 is used for the MCA process described in Appendix A.1. For each iteration (i.e., specification of aspiration and  
402 reservation values for each criterion) the following actions are executed:

- 403 • The interactively specified values of  $\bar{q}_k$  and  $\underline{q}_k$  are stored in a common data-base (DB).
- 404 • The GUI calls the multi-criteria (MC)-solver, which generates the MC-part of the MCA, and queues the corre-  
405 sponding Optimization Task (OT).
- 406 • A dedicated utility called Task Manager (TM) distributes the OTs over the workstations with the available  
407 optimizers (same solvers as used for the single criterion model optimization).

- 408 • A dedicated MC optimization-solver merges the MC-part with the core model into either the MPS standard file  
409 or a GAMS format model, and invokes the relevant solver for solving the corresponding LP problem. For the  
410 MCA of the SEWP model, the CPLEX solver is used.
- 411 • After the LP problem is solved, the MCO-solver extracts from the provided solution file values of criteria and  
412 uploads them into the DB.
- 413 • After the solution is uploaded into the DB, the MC-solver computes the elements of the graphical solution  
414 representation, and marks in the DB as available for the user.
- 415 • The status of computations related to each MCA iteration is updated in the DB by each software component.  
416 The GUI checks this status whenever the user wants to explore the results of the corresponding iteration, and  
417 provides the user with access to the relevant selected iteration of efficient solutions or to the information about  
418 the computation status of the iteration.
- 419 • In addition to the analysis in the criteria space typically supported by the GUI of the MCA tools, the user has  
420 access to full solutions provided by the solver of the optimization task. These solution can therefore be used for  
421 model-specific analysis (a sample of such analysis is shown in Section 4).

## 422 Acknowledgements

423 SCP was supported in part by a post-graduate scholarship from the Natural Sciences & Engineering Research  
424 Council of Canada. ND acknowledges with thanks funding of this project by the Deanship of Scientific Research  
425 (DSR), King Abdulaziz University, Jeddah, under grant no. (1-135-36-HiCi).

## 426 References

- 427 [1] IEA, Chapter 17: Water for Energy, in: World Energy Outlook, International Energy Agency, 2012, pp. 1–33.
- 428 [2] S. G. Rothausen, D. Conway, Greenhouse-gas emissions from energy use in the water sector, *Nature Climate Change* 1 (4) (2011) 210–219.
- 429 [3] A. J. Seebregts, G. A. Goldstein, K. Smekens, Energy/environmental modeling with the MARKAL family of models, in: *Operations Research*  
430 *Proceedings 2001*, Springer, 2002, pp. 75–82.
- 431 [4] L. Schratzenholzer, A. Miketa, K. Riahi, R. A. Roehrl, Achieving a sustainable global energy system: Identifying possibilities using long-term  
432 energy scenarios, Edward Elgar Publishing, 2004.
- 433 [5] M. Howells, H. Rogner, N. Strachan, C. Heaps, H. Huntington, S. Kypreos, A. Hughes, S. Silveira, J. DeCarolis, M. Bazillian, et al.,  
434 OSeMOSYS: The open source energy modeling system: An introduction to its ethos, structure and development, *Energy Policy* 39 (10)  
435 (2011) 5850–5870.
- 436 [6] S. Atilhan, A. B. Mahfouz, B. Batchelor, P. Linke, A. Abdel-Wahab, F. Nápoles-Rivera, A. Jiménez-Gutiérrez, M. M. El-Halwagi, A systems-  
437 integration approach to the optimization of macroscopic water desalination and distribution networks: a general framework applied to Qatar's  
438 water resources, *Clean Technologies and Environmental Policy* 14 (2) (2012) 161–171.
- 439 [7] M. Fripp, Switch: a planning tool for power systems with large shares of intermittent renewable energy, *Environmental science & technology*  
440 46 (11) (2012) 6371–6378.

- 441 [8] E. H. Beh, G. C. Dandy, H. R. Maier, F. L. Paton, Optimal sequencing of water supply options at the regional scale incorporating alternative  
442 water supply sources and multiple objectives, *Environmental Modelling & Software* 53 (2014) 137–153.
- 443 [9] M. T. van Vliet, S. Vögele, D. Rübhelke, Water constraints on European power supply under climate change: Impacts on electricity prices,  
444 *Environmental Research Letters* 8 (3) (2013) 035010.
- 445 [10] S. J. Pereira-Cardenal, H. Madsen, K. Arnbjerg-Nielsen, N. Riegels, R. Jensen, B. Mo, I. Wangenstein, P. Bauer-Gottwein, Assessing climate  
446 change impacts on the Iberian power system using a coupled water-power model, *Climatic Change* (2014) 1–14.
- 447 [11] A. Santhosh, A. M. Farid, K. Youcef-Toumi, Real-time economic dispatch for the supply side of the energy-water nexus, *Applied Energy* 122  
448 (2014) 42–52.
- 449 [12] M. Bekchanov, C. Ringler, A. Bhaduri, M. Jeuland, How would the Rogun Dam affect water and energy scarcity in Central Asia?, *Water*  
450 *International* 40 (5-6) (2015) 856–876.
- 451 [13] S. J. Pereira-Cardenal, B. Mo, A. Gjelsvik, N. D. Riegels, K. Arnbjerg-Nielsen, P. Bauer-Gottwein, Joint optimization of regional water-power  
452 systems, *Advances in Water Resources* 92 (2016) 200–207.
- 453 [14] N. Buras, Integration of Water Resource Constraints in Energy Models, Tech. rep., Systems Optimization Laboratory, Department of Opera-  
454 tions Research, Stanford University (1979).
- 455 [15] A. F. P. de Lucena, R. Schaeffer, A. S. Szklo, Least-cost adaptation options for global climate change impacts on the Brazilian electric power  
456 system, *Global Environmental Change* 20 (2) (2010) 342–350.
- 457 [16] M. Webster, P. Donohoo, B. Palmintier, Water-CO<sub>2</sub> trade-offs in electricity generation planning, *Nature Climate Change* 3 (12) (2013) 1029–  
458 1032.
- 459 [17] S. Bouckaert, E. Assoumou, S. Selosse, N. Maïzi, A prospective analysis of waste heat management at power plants and water conservation  
460 issues using a global TIMES model, *Energy* 68 (2014) 80–91.
- 461 [18] S. M. Cohen, K. Averyt, J. Macknick, J. Meldrum, Modeling climate-water impacts on electricity sector capacity expansion, in: ASME 2014  
462 Power Conference, American Society of Mechanical Engineers, 2014, pp. 1–8.
- 463 [19] N. Johnson, O. Fricko, S. Parkinson, K. Riahi, Energy sector adaptation in response to water scarcity, in: AGU Fall Meeting, American  
464 Geophysical Union, 2015.
- 465 [20] S. C. Parkinson, N. Djilali, Robust response to hydro-climatic change in electricity generation planning, *Climatic Change* 130 (4) (2015)  
466 475–489.
- 467 [21] Z. Khan, P. Linares, J. García-González, Adaptation to climate-induced regional water constraints in the Spanish energy sector: An integrated  
468 assessment, *Energy Policy* 97 (2016) 123–135.
- 469 [22] J. Matsumoto, L. W. Mays, Capacity expansion model for large-scale water-energy systems, *Water Resources Research* 19 (3) (1983) 593–  
470 607.
- 471 [23] A. Dubreuil, E. Assoumou, S. Bouckaert, S. Selosse, N. Maïzi, Water modeling in an energy optimization framework: The water-scarce  
472 Middle East context, *Applied Energy* 101 (2013) 268–279.
- 473 [24] M. D. Bartos, M. V. Chester, The conservation nexus: Valuing interdependent water and energy savings in Arizona, *Environmental Science*  
474 *& Technology* 48 (4) (2014) 2139–2149.
- 475 [25] M. Welsch, S. Hermann, M. Howells, H. H. Rogner, C. Young, I. Ramma, M. Bazilian, G. Fischer, T. Alfstad, D. Gielen, Adding value with  
476 CLEWS: Modelling the energy system and its interdependencies for Mauritius, *Applied Energy* 113 (2014) 1434–1445.
- 477 [26] N. Al-Qattan, M. Ross, A. K. Sunol, A multi-period mixed integer linear programming model for water and energy supply planning in Kuwait,  
478 *Clean Technologies and Environmental Policy* 17 (2) (2015) 485–499.
- 479 [27] W. Huang, D. Ma, W. Chen, Connecting water and energy: Assessing the impacts of carbon and water constraints on China’s power sector,  
480 In Press, *Applied Energy* (2016) 1–8.
- 481 [28] S. C. Parkinson, N. Djilali, V. Krey, O. Fricko, N. Johnson, Z. Khan, K. Sedraoui, A. H. Almasoud, Impacts of groundwater constraints on  
482 Saudi Arabia’s low-carbon electricity supply strategy, *Environmental Science & Technology* 50 (4) (2016) 1653–1662.
- 483 [29] Y. Saif, A. Almansoori, A capacity expansion planning model for integrated water desalination and power supply chain problem, *Energy*

- 484 Conversion and Management 122 (2016) 462–476.
- 485 [30] D. L. McCollum, V. Krey, K. Riahi, An integrated approach to energy sustainability, *Nature Climate Change* 1 (9) (2011) 428–429.
- 486 [31] D. L. McCollum, V. Krey, K. Riahi, P. Kolp, A. Grubler, M. Makowski, N. Nakicenovic, Climate policies can help resolve energy security  
487 and air pollution challenges, *Climatic Change* 119 (2) (2013) 479–494.
- 488 [32] M. Makowski, Management of attainable tradeoffs between conflicting goals, *Journal of Computers* 4 (10) (2009) 1033–1042.
- 489 [33] L. Duckstein, S. Opricovic, Multiobjective optimization in river basin development, *Water Resources Research* 16 (1) (1980) 14–20.
- 490 [34] M. Makowski, L. Somlyódy, D. Watkins, Multiple criteria analysis for water quality management in the Nitra basin, *Journal of the American  
491 Water Resources Association* 32 (5) (1996) 937–951.
- 492 [35] S. Pohekar, M. Ramachandran, Application of multi-criteria decision making to sustainable energy planning: A review, *Renewable & Sus-  
493 tainable Energy Reviews* 8 (4) (2004) 365–381.
- 494 [36] M. Lehtveer, M. Makowski, F. Hedenus, D. McCollum, M. Strubegger, Multi-criteria analysis of nuclear power in the global energy system:  
495 Assessing trade-offs between simultaneously attainable economic, environmental and social goals, *Energy Strategy Reviews* 8 (2015) 45–55.
- 496 [37] A. Wierzbicki, M. Makowski, J. Wessels, et al., *Model-based decision support methodology with environmental applications*, Kluwer Aca-  
497 demic Publishing, 2000.
- 498 [38] D. Jornada, V. J. Leon, Robustness methodology to aid multiobjective decision making in the electricity generation capacity expansion  
499 problem to minimize cost and water withdrawal, *Applied Energy* 162 (2016) 1089–1108.
- 500 [39] Y. Zhou, R. S. Tol, Evaluating the costs of desalination and water transport, *Water Resources Research* 41 (3).
- 501 [40] B. R. Phillips, R. S. Middleton, SimWIND: A geospatial infrastructure model for optimizing wind power generation and transmission, *Energy  
502 Policy* 43 (2012) 291–302.
- 503 [41] A. S. Stillwell, M. E. Webber, Geographic, technologic, and economic analysis of using reclaimed water for thermoelectric power plant  
504 cooling, *Environmental Science & Technology* 48 (8) (2014) 4588–4595.
- 505 [42] V. C. Tidwell, J. Macknick, K. Zemlick, J. Sanchez, T. Woldeyesus, Transitioning to zero freshwater withdrawal in the US for thermoelectric  
506 generation, *Applied Energy* 131 (2014) 508–516.
- 507 [43] E. Ibanez, T. Magee, M. Clement, G. Brinkman, M. Milligan, E. Zagona, Enhancing hydropower modeling in variable generation integration  
508 studies, *Energy* 74 (2014) 518–528.
- 509 [44] S. Sattler, J. Macknick, D. Yates, F. Flores-Lopez, A. Lopez, J. Rogers, Linking electricity and water models to assess electricity choices at  
510 water-relevant scales, *Environmental Research Letters* 7 (4) (2012) 045804.
- 511 [45] S. M. Lele, Improved algorithms for reservoir capacity calculation incorporating storage-dependent losses and reliability norm, *Water Re-  
512 sources Research* 23 (10) (1987) 1819–1823.
- 513 [46] N. Johnson, M. Strubegger, M. McPherson, S. C. Parkinson, V. Krey, P. Sullivan, A reduced-form approach for representing the impacts of  
514 wind and solar PV deployment on the structure and operation of the electricity system, *Energy Economics In Press* (2016) 1–11.
- 515 [47] A. P. Wierzbicki, The use of reference objectives in multiobjective optimization, in: *Multiple Criteria Decision Making Theory and Applica-  
516 tion*, Springer, 1980, pp. 468–486.
- 517 [48] J. Granat, M. Makowski, Interactive specification and analysis of aspiration-based preferences, *European Journal of Operational Research*  
518 122 (2) (2000) 469–485.
- 519 [49] M. Makowski, A. P. Wierzbicki, Modeling knowledge: Model-based decision support and soft computations, in: *Applied Decision Support  
520 with Soft Computing*, Springer, 2003, pp. 3–60.
- 521 [50] M. Makowski, H. Ren, IIASA Integrated Modeling Environment Project - Multiple Criteria Model Analysis (MCMA),  
522 [www.iiasa.ac.at/~marek/mca\\_doc/mcma.html](http://www.iiasa.ac.at/~marek/mca_doc/mcma.html), last accessed: 2016-06-12 (2016).
- 523 [51] IEA, International Energy Agency Statistics: Saudi Arabia, [www.iea.org/countries/non-membercountries/saudi Arabia/](http://www.iea.org/countries/non-membercountries/saudi Arabia/), last accessed: 2015-  
524 06-10 (2014).
- 525 [52] T. Gleeson, Y. Wada, M. F. Bierkens, L. P. van Beek, Water balance of global aquifers revealed by groundwater footprint, *Nature* 488 (7410)  
526 (2012) 197–200.

- 527 [53] B. C. O'Neill, E. Kriegler, K. L. Ebi, E. Kemp-Benedict, K. Riahi, D. S. Rothman, B. J. van Ruijven, D. P. van Vuuren, J. Birkmann, K. Kok,  
528 et al., The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century, *Global Environmental*  
529 *Change*.
- 530 [54] K. Samir, W. Lutz, The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all  
531 countries to 2100, *Global Environmental Change*.
- 532 [55] R. Dellink, J. Chateau, E. Lanzi, B. Magne, Long-term economic growth projections in the Shared Socioeconomic Pathways, *Global Envi-*  
533 *ronmental Change*.
- 534 [56] L. Jiang, B. C. O'Neill, Global urbanization projections for the Shared Socioeconomic Pathways, *Global Environmental Change*.
- 535 [57] O. K. Ouda, Impacts of agricultural policy on irrigation water demand: A case study of Saudi Arabia, *International Journal of Water Resources*  
536 *Development* 30 (2) (2014) 282–292.
- 537 [58] S. Chowdhury, M. Al-Zahrani, Characterizing water resources and trends of sector wise water consumptions in Saudi Arabia, *Journal of King*  
538 *Saud University-Engineering Sciences* 27 (1) (2015) 68–82.
- 539 [59] K. Riahi, F. Dentener, D. Gielen, A. Grubler, J. Jewell, Z. Klimont, V. Krey, D. McCollum, S. Pachauri, S. Rao, *Global Energy Assessment*  
540 *Chapter 17: Energy pathways for sustainable development*.
- 541 [60] J. Swisher, G. Martino-Jannuzzi, R. Redlinger, *Tools and Methods for Integrated Resource Planning: Improving Energy Efficiency and*  
542 *Protecting the Environment*, Tech. rep., United Nations Environment Programme (1997).