Planning of Food-Energy-Water-Waste (FEW2) nexus for sustainable development

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Abstract

It is critical for reliable infrastructure planning to address the Food-Energy-Water-Waste (FEW2) nexus at system level. This paper presents the applicability of the systematic modelling platform resilience.io across water, energy and waste sectors with focus on waste-to-energy pathway, aiming to establish the optimal FEW2 nexus based on economic and environmental indicators. A rich array of technology options, including water production facilities, clean energy technologies and waste-to-energy conversions are evaluated to meet the demand of water and energy (mainly gas and electricity), and the treatment requirement of waste and wastewater. A case study of Hunter Valley, the largest region in Australia, is presented in this study, featuring the supply and demand context of developed countries. A full set of scenarios, including business-as-usual (BAU), water and wastewater, power plant decommission, waste-to-energy and policy intervention, is created to present FEW2 nexus from the perspective of individual nodes and the whole system. The results signal the benefits of biogas and syngas generation from anaerobic digestion and gasification for waste-to-energy pathway, alongside findings in water and energy sectors. The outcome of this analysis can then form the foundation of regional planning involving relevant stakeholders, with the modelling tools supporting scenario evaluation and collaborative learning to reach consensus in view of different performance indicators.

Background

The Food-Energy-Water-Waste (FEW2) Nexus concept characterizes the interconnected generation, allocation and consumption processes of the four elements. As shown in Figure 1, when generating, allocating and consuming one of food, energy and water, it is impossible to avoid generating, allocating and consuming the other two [1]. Unconsumed food mostly turns into food waste, while waste management processes also involve the generation and consumption of both water and energy [2]. The inherently intertwined relationship amongst the four indicates the necessity of utilizing the nexus concept as a tool, to address problems encountered when attempting to achieve sustainability for individual elements.

According to the Food and Agriculture Organization of United Nations in 2011, it is estimated that about 1.3 billion tonnes of global food is wasted or lost, which accounts for approximately one third of total food production [4]. Wasting food means wasting water and energy, since producing, processing and consuming of food contribute to about 70% of global water withdrawn and 30% global energy consumed [5]. Besides post-consumer food waste, enormous organic waste is also generated from food production processes. About 60% of a slaughtered animal mass cannot be converted to edible flesh and becomes abattoir waste. In the United State, the annual abattoir waste generation is about 1.4 billion tonnes [6]. Animal's manure is another example of waste generation from food production, amounting to approximately 2 billion ton per year in the United State [7], which is about 300 times to the human faeces generated in American [8]. Approximately 330 km³ per year of municipal wastewater is generated globally, a significant amount of which is food waste from dairy processing and beverage manufacturing [9]. In 2016, the World Bank estimated 2.01 billion tonnes of municipal solid waste (MSW) is generated in the city, much of which is discarded food waste. With rapid urbanization and population growth, the number is projected to reach 3.40 billion tonnes per year by the middle of this century [10]. The waste streams are viewed as unwanted hitches by waste generators, but also rich organic feedstocks for waste processors. Within the FEW2 nexus, wastes may be further processed to produce a combination of valuable products and energy resources including heat, electricity and gas [11]. Waste-to-Energy (WtE) technologies is reported by World Energy Council as a viable solution for waste treatment. Meantime, continuing population growth is expected to increase global energy demand by at least 27% from 2010 to 2050 [12]. The need to expand the share of clean energy also drives the waste treatment towards WtE pathway. The selection and allocation of WtE facilities are constrained by the interrelated resources within FEW2 nexus, including their spatial distribution, demand profile and connected transportation network, and the capacity and mass and energy balance of technologies. The financial and environmental feasibility of planned facilities should also be evaluated under a continuous time scale to ensure long-term sustainability [13]. A system approach to addressing these concerns would stand a unique position to support decision-making process for infrastructure planning, which is often realized by computational modelling, a prevailing tool to account for the complex interconnection within FEW2 nexus while comprehending the need of being eco-friendly and economically feasible [14, 15].

Previously, researchers have conducted system analysis on demand and supply optimization of sub-component(s) of the FEW2 nexus. Complete urban water system models have found to be developed in recent years. Rozos and Makropoulos's Urban Water Optioneering Tool (UWOT) is built to simulate the whole water supply system from household demand to reservoir, while tracing wastewater from household generation, through wastewater treatment system, to the water bodies [16]. Behzadian et al.'s WaterMet2 is another comprehensive water and wastewater model, which includes the management of supply and demand balances, network flow, energy usage and greenhouse gas (GHG) emission [17]. A review of prior study also shows the topic of energy system modelling is becoming more and more popular. Keirstead et al. reviewed a total of 219 studies and identified a major challenge that the transportation variable between regions is often excluded in system design models [18]. Many studies examined the interaction between two nodes in the FEW2 nexus [1], such as water and energy systems [19] and waste-to-energy systems [20]. Nonetheless, an emerging trend is observed to model the system by connecting all the nodes to exploit potential synergies [21, 22]. Garcia and You identified system engineering as a tool for waste management under FEW2 nexus [23]. This is in line with Kibler et al.'s conclusion that a FEW2 system approach can improve the benefits across all the underlying sectors [24]. As opposed to system engineering, system modelling approach provides insights on various potential options prior to the implementation of system engineering [25]. It is thus extremely prevalent to bridge the gap on incorporating FEW2 system modelling into decision-making tools, which should also resolve supply and demand details in a spatial and temporal scale.

Previous work by Triantafyllidis et al., Wang et al. and Bieber et al. has demonstrated the use of an integrated platform, resilience.io, to deliver sustainable urban planning and inform decision making [3, 26, 27]. The platform is integrated with three sub-modules, which are social-demographic forecasting model, agent-based model (ABM) and resource technology network (RTN) optimization. The framework combines the functionality of the above three, allowing demand profiles simulation based on social-demographic scenarios, which in turn serves as groundwork for supply optimization and planning [28]. Prior researchers have proved the effectiveness of this holistic methodology and platform in supporting resilient decision-making in the context of developing country. The modelling of urban energy system (UES), energy-water-food (EWF) nexus and waste-to-energy system by using resilience.io platform has been

conducted and the Greater Accra Metropolitan Area (GAMA) of Ghana is used as the region of case study [3, 26-29]. The results of these studies provide Ghana with various insights in the field of water supply, energy deployment and waste treatment.

This paper seeks to present the system modelling of FEW2 nexus via resilience.io platform, to achieve the objective of efficient decision making in regional infrastructure planning. A scenarios-based approach is highlighted in this work, alongside assessment of prevalent policies. The energy sector within FEW2 nexus includes both electricity and gas as energy resources and allows conversion between the two, with the impact of energy conversion accounted [30]. Diverted from the previous work, a case study of developed country will be discussed to showcase the FEW2 system modelling from another perspective. In contrast to developing countries, cities and regions of developed countries are often equipped with complete and functional infrastructure such as water and waste treatment facilities and their corresponding networks [31]. This would increase the complexity of system modelling as the baseline scenario must be prudently configured to reflect the supply and demand balances of the existing system. Furthermore, developed countries is often subject to various policies constraints. For example, nuclear energy is banned in Australia due to its lack of public support, despite that about one-third of global uranium is deposited in the country [32, 33]. These could partly explain why developed countries are rarely involved in the case study of system modelling research. However, studies have shown the historical GHG contribution of developed countries takes about 60% from 1850 to 2005 [34], while in 2011, developed countries still contribute to 37% of global emission [35]. The statistics indicate the responsibility and need to reduce emission in developed countries, which can be accommodated by sustainable planning via system modelling, with another important performance indicator, financial feasibility, included in the matrix as well. The applicability of resilience.io platform in the context is demonstrated in this study, where possible systematic solutions for Hunter Valley region in Australia is examined under several scenarios.

Hunter Valley is Australia's largest region. With Newcastle's large metropolitan area on the Pacific coast, it resembles a microcosm of the broader Australian economy, with notable sectoral activities including food and energy production, natural resources and coal mining, defence industry, and service economies [36]. Water security remains a vital, strategic issue for the region, with water services in Lower Hunter undertaken through the public water authority, Hunter Water, which services nearly 600,000 users [37]. Although the region has significant groundwater resources, water supplies have, in the past, been vulnerable to drought events [38]. With increasing population levels forecasted, and a potential for decreased water yield with higher variability associated with climate change, Hunter Water and government agencies are considering a range of strategic options to address the region's water security over the medium and long term. Likewise, the region's projected population and industrial growth will result in an increase in water and energy consumption per capita. The Hunter Regional Plan 2036 calls for the diversification of the energy sector to take advantage of "the region's potential to be a major hub for next-generation power". Given agreements to increase the proportion of renewables in the energy matrix and with two major coal-powered thermal power stations being scheduled to close in 2022 and 2035 (Liddell and Bayswater), the regional government promises to promote initiatives that can combine economic and energy diversification [39]. Waste-to-Energy is identified by local agencies as the most promising clean energy solution, as the increase of solid waste and wastewater generation also requires the region to expand its waste management capacity and upgrade its efficiency to reduce costs and meet climate targets [40].

To recover energy from various waste streams, anaerobic digestion (AD) of organic solid waste is a mature technology that plays a crucial role for its biogas (methane, 50 – 75%) production and pathogen destruction characteristics [41]. It also minimizes the residual solids for disposal and the odour of remaining putrescible substance [42]. In addition, co-digestion and thermal hydrolysis pre-treatments are interesting options to improve the yields of treating solid wastes and increase economic advantages [41]. AD and its variations are incorporated to the model in both centralized and decentralized scales to assess the feasibility of all the possibilities. Another waste degradation solution, gasification, is also demonstrated as one of the most efficient and eco-friendly technologies for waste-to-energy conversion [43]. Plasma and fluid-bed gasification are included in this model [44, 45]. The products of gasification processes are known as syngas. Both syngas and biogas are modelled to go through pressure swing adsorption (PSA) process for purification and upgrading, so that they can be injected into natural gas grid for direct supply of energy [46]. The generated biogas and syngas are also modelled as fuel for combined heat and power generation. Such a combination of end-uses allows the model to allocate WtE technologies and gas-to-electricity conversion in the most efficient way based on the individual demand of gas and electricity.

This work includes the exploration of total five scenarios, namely "business as usual (BAU)", "water and wastewater", "Liddell and Bayswater power plant decommission", "waste-to-energy" and "policy interventions" (Figure 2). Overall, the effectiveness of resilience.io platform in developed country is demonstrated by the regional study of Hunter Valley. Together with prior case studies of Ghana, the system modelling framework presents its robustness in various contexts of application.

Methods

This section describes the overall modelling framework used in this study as well as the main inputs and assumptions for the systems model implemented for the Hunter Region. Afterwards this model is applied to the case study under various scenarios.

2.1 resilience.io modelling approach

The resilience.io platform was developed to study urban or regional planning under a range of long-term scenarios. These scenarios can be designed to reflect policy changes, regional connections, economic background and advances in technologies, while providing insights on the optimal solutions of long-term development, that is, to meet local resource demands in a cost-effective and sustainable way [26]. The resilience.io platform provides the following three modules in series: sociodemographic model to forecast population and business development, agent-based model to simulate spatio-temporal activities and generate resource demands, and resource-technology-network optimization to find a matrix of technologies with correct location and size, to meet all the demands [3]. The final goal is to plan investment and operational strategies based on economics metrics (e.g. capital expenditure, operating expenditure, taxes, etc) and environmental considerations (e.g. greenhouse gas emission), while connecting multiple levels in a system approach (Figure 3). These

modules can be used together to build a scenario, or they can be used independently, for example by supplying demand data from other sources as input to the optimization module.

2.2 Model for the Hunter Region

To test the feasibility of studying the nexus between food, water, energy and (materials discarded as) waste for the Hunter Region with this platform, we have implemented a prototype model for the region. This model has been applied to demonstrate how the systems approach could be used to identify opportunities based on included material flows and conversion technologies (see Section 2.3). Resources and discarded materials available are simulated or included from published data and regional forecasts, with specific technologies—with their economic and environmental performance—selected as input for the resource-technology-network optimization model.

Using this approach, a first prototype model has been set up for the Hunter Region (see Figure 12 for the case study area) to simulate the current water demand, supply and networks and explore potential future designs and interventions to take advantage of synergies at the FEW2 nexus. Key resources that were incorporated in the model include potable water, non-drinking water (industrial use), source water, electricity, gas, domestic waste (municipal solid waste, sewage), agricultural waste and other organic waste, biosolid, carbon dioxide, etc. Figure 4 shows example processes that could be set up in the model as process blocks to consider generation of energy from wastes. The combinations of feedstocks and technologies incorporated in this case study are listed in Table 3 with specific technologies that are incorporated in the model including both existing and potential new installations and conversion processes described in the waste-to-energy case study section. The optimization model then selects which of these options can be attractive from an economic and environmental perspective, under the constraints of land-use (e.g. land types and availability) and regional transportation (e.g. limited or costly resource sharing for non-adjacent areas). The results provide urban development plans for capital allocation on infrastructure and new technologies, as well as operation plans such as production rate and transportation rate schedules, in order to meet demands and minimize costs.

2.3 Optimization Model Structure

To address the interrelationship of the nexus between food, water, energy and waste for the Hunter Region, the resource-technology-network optimization model is formulated to reflect the resource flows as well as material and energy balance of conversion technologies. The optimization problem is defined as a Mixed-Integer Linear Programming (MILP) model. The objective function is defined to be a weighted sum of capital expenditures, operating expenditures, and environmental impacts. Greenhouse gas emission is included as the contributor to environmental costs, with its value monetized by carbon credit prices. Existing and new technologies are introduced as input-output flow vectors. Each technology entry is represented by an array of resources, waste, energy, labour and CO₂ emissions with their values normalized to facility capacity. Imports and exports are simulated in the entire system to accommodate various cross-boundary scenarios (e.g. Electricity generator supplying external demands, treated waste effluent discharged into rivers, and solid waste landfill). Model constraints can also be applied to restrict flows and define upper bounds for resource transportation. The model objective function is shown in Equation (1) and the related constraints are also provided below.

Indices and parameters

$i, i'(\text{alias})$	zone/cell/district/region
j	type of technology
m	metrics as CAPEX, OPEX, CO2
r	type of resources (material or energy)
t	minor time period as fraction of a single day
tm	major time period as years
$IM(r, i, t, tm)$	import of resource
$P(j, i, t, tm)$	production rate of technologies
$Q(r, i, i', t, tm)$	flow of r from i to i'
$RS(r, i, t, tm)$	net surplus of r in i in time period t of tm
$VM(m, tm)$	total value of m in major time period tm
Z	the objective function
$INV(j, i, tm)$	number of units of j invested in time tm
$N(j, i, tm)$	number of tech j in cell i in tm
$YQ(r, i, i', t, tm)$	whether to allow transportation of r from i to i'
$YIM(r, i, t, tm)$	whether to allow import/export of r in district i
$dist(i, i')$	distance from district i to i'
$MU(j, r)$	rate of r production per unit of j
$ObjWt$	objective function weights
PHI	hours assigned for a year
$Q_{\max}$	max flow of resources
$IM_{\max}$	max import/export flow of resources
$VI(r, m)$	import value of r/m
$VIJ(j, m)$	technology investment coefficient in m
$VPJ(j, m)$	technology process coefficient in m
$VQ(r, m)$	transportation coefficient per km of r/m
$X(i)$	X coordinate of i , in km
$Y(i)$	Y coordinate of i , in km
$dist(i, i')$	$\sqrt{(X_i - X_{i'})^2 + (Y_i - Y_{i'})^2}$
$abs(x)$	absolute value of x

$$\text{Objective Function, } Z = \sum_{m, tm} ObjWt(m, tm) \cdot VM(m, tm) \quad (1)$$

$$VM(m, tm) = \sum_{j, i} VIJ(j, i, m) \cdot INV(j, i, tm)$$

$$\begin{aligned}
& + \sum_{j, i, t} VPJ(j, m) \cdot P(j, i, t, tm) \\
& + \sum_{r, i, i', t} VQ(r, m) \cdot dist(i, i') \cdot Q(r, i, i', t, tm) \cdot YQ(r, i, i', t, tm) \\
& + \sum_{r, i, t} VI(r, m) \cdot abs(IM(r, i, t, tm)) \cdot YIM(r, i, t, tm), \quad \forall r, m, tm
\end{aligned}$$

Constraints:

$$\text{Technology increament, } N(j, i, tm) = N(j, i, tm - 1) + INV(j, i, tm) \quad \forall j, i, tm$$

$$\text{Flow constraints, } Q(r, i, i', t, tm) - \frac{Q_{\max}}{(PHI(t)/8760)} \cdot YQ(r, i, i', t, tm) \leq 0 \quad \forall r, j, i, t, tm$$

$$\text{Import/export, } abs(IM(r, i, t, tm)) - IM_{\max} \cdot YIM(r, i, t, tm) \leq 0 \quad \forall r, j, i, t, tm$$

$$\begin{aligned}
\text{Mass Balance, } RS(r, i, t, tm) &= \sum_j MU(j, r) \cdot P(j, i, t, tm) \\
& + \sum_{i'} Q(r, i, i', t, tm) \\
& - \sum_{i'} Q(r, i', i, t, tm) \\
& + IM(r, i, t, tm) \quad \forall r, i, t, tm
\end{aligned}$$

As shown in above equations, the objective function is a weighted average of metrics (m) including capital investment (VIJ), operating costs (VPJ), resource transportation (VQ) and resource import/export costs of resources (VI). The optimization model also implements various constraints to model restriction encountered in urban planning. At each time period and spatial zone, material and energy balance constraints are introduced to match demand value. Flow limits for waste transportation, water pipes and electricity grid delivery are also imposed. Import and export limits can be applied to simulate resource shortage scenarios (e.g. water shortage in section 3.3). Besides single period planning, the model output of a time period serves as the input of the next period. Together with the evolution of population status and demand behaviours predicted in forecasting model, optimization process for 20 years is iterated to achieve future planning at future conditions. The open-source GUN Linear Programming Kit (GLPK) is used to solve the optimization problem.

Part A to F in the supporting information list the key input data and detailed assumptions applied in the modelling, together with the data sources used in this study.

Results And Discussion

This section describes the five scenarios explored in this study, using the systems model for the Hunter region described above. Each scenario is considered at the current situation (based on 2016 data as a baseline) as well as forecasts at 5-year intervals until 2036 following the timeline of the 20-year regional blueprint published by the NSW government. The FEW2 nexus has been built up via scenario analysis and each scenario presents the system from the perspective of either water and wastewater, energy, waste or system-wise performance.

3.1 Scenarios explored in this study

1. Business-as-usual (BAU); a baseline scenario using the current infrastructure in the region for water and energy (electricity and gas),
2. Water and wastewater scenario, which includes introduction of new technology, e.g. water reclamation, and constraints on the use of raw source water,
3. Closure of the coal-fired Liddell and Bayswater power stations in the near future, following Hunter Regional Plan 2036,
4. Waste to energy scenario (WtE), in which biosolids, municipal solid wastes, agricultural wastes and other organic wastes are considered as the (co-)feedstock of renewable energy generation using anaerobic digestion (with thermal hydrolysis), incineration, gasification and pyrolysis, and
5. Economic/policy scenarios, including changes of feed-in-tariffs and carbon credit to study the sensitivities of waste-to-energy.

3.2 Business as usual (BAU) scenario

Business as usual (BAU) scenario serves as a basis to analyse the changes in other scenarios. The current network for potable water production and wastewater treatment is established in this scenario. Similarly, power stations inside Hunter Region (Liddell, Bayswater, Eraring and Vales Point) are modelled to supply all the electricity demand in 2016, which is about 10% of the total capacity. The rest is modelled to leave the system to support regions outside the study area. The existing facilities will be carried out to other scenarios as necessary constituents of FEW2 nexus. Details of existing facilities can be found in Supporting Information Part E.

In terms of waste management, biosolids management cost is modelled by referencing BAU options provided by GHD Pty Ltd [49]. The input waste streams are assumed to leave the system through recycle/recovery and landfill at different prices. The biosolids disposal cost via land application program is included in the system, based on cost data provided by Hunter Water. Other than biosolids, MSW will have a landfill levy of \$78.20 dollar per tonne. This figure is lower than the rates in, for example, Newcastle, but the smaller value is selected for the system to ensure the conservativity of the potential cost savings of avoiding landfill.

For other organic feedstocks, it is understood that depending on specific feedstock types, various treatment facilities are currently available to accept organic wastes with certain gate fee, which is unclear at this time point. In that case, post-consumer waste is assumed to be landfilled according to MRA Consulting Group [50]. Other organic wastes are assumed to be recovered with certain gate fees charged by waste processors. The assumptions for gate fees of various feedstocks are listed in below table.

The results of business as usual scenario show that no investment is needed to supply various resource demand in the Hunter Region, except for potential pipeline network construction during certain time intervals. Current infrastructure is more than sufficient to satisfy 100% demand. However, since no WtE treatment facilities are present, disposal of waste incurs operating cost of the system.

GHG emission exhibits steady growth from 2016 to 2036, mainly because the demand profile increases across intervals. A higher capacity for various existing facilities is required to satisfy all the demand. Figure 5 displays the GHG emission for BAU. Note that the values include all the existing facilities of water and wastewater treatment, power stations, etc.

The capital expenditure (CAPEX), operating expenditure (OPEX) and present value of cost related to WtE are specifically extracted from the background facilities (including existing water treatment plants and power stations) to compare with WtE scenarios. The values are summarised in Table 2.

3.3 Water and wastewater scenario

This scenario extends the BAU scenario and present the modelled FEW2 nexus from the perspective of water and wastewater. In BAU, the results show no investment is compulsory to satisfy regional water demand and wastewater treatment capacity from 2016 to 2036, which is based on an implicit assumption that raw source water resource can be extracted without a limit for drinking water production. The assumption is valid in most situations, considering the sub-tropical climate in Hunter, with annual rainfall at about 870 mm across the region [51]. Nonetheless, according to Hunter Water, the level of water storage dams responsible for the region decreases faster than usual during hot, dry season due to relatively high evaporation rates and shallow dam storages [52]. Figure 6 taken from Hunter Water shows the forecasting of storage levels under three scenarios, as well as the situations when water restrictions may apply.

The water storage outlook indicates that dam level will decrease to 60% of total storage and hit level 1 water restrictions under low rainfall scenario at July of 2019. Level 1 restrictions refers to forbidden sprinkler use for household and business users [53]. In this scenario, the critical water shortage level caused by

unprecedented drought conditions is simulated in the model. Constraints are set to limit the extraction of raw water to ensure at least 60% of total dam storage. A set of options for water supply is included in this analysis such as water reclamation technology, desalination and water import.

NEWater, produced by Singapore's Public Utilities Board (PUB), is modelled as one of the water reclamation technologies in this study. Started in 1970s, the NEWater technology currently supplies up to 40% of Singapore water demand. NEWater plants collect treated used water from standard reclamation facilities and then apply 3-step treatment to upgrade the water quality. This includes microfiltration to filter out microscopic particles, reverse osmosis to remove undesirable contaminants and ultraviolet disinfection to eradicate any residual organisms [54]. The produced water is sent for non-portable use (e.g. industrial use and air-con cooling) and non-direct portable use at dry seasons (i.e. blending with raw water in reservoir). Hence, NEWater is also considered as potential solutions for drought conditions in Hunter for its ability to produce additional raw water and append wastewater treatment capacity. It is thus configured in the model to produce both raw water and non-drinking water. Another option, desalination, is also included to produce drinking water directly. Together with water import, the optimization model evaluates the economic and environmental performance of all options to provide the best combination.

The results indicate NEWater outperforms desalination and other options as it provides raw water to maximize the capacity of existing water treatment plant and delivers non-drinking water for industrial and agricultural use at the same time. Desalination and raw water import are not favoured by the model for their relatively high operating costs or prices. Figure 7 shows the production rate of NEWater and recycled water to wastewater ratio over 20 years. About 35% of wastewater need to be recycled in 2036 to prevent the dam level from falling below 60% at extremely drought periods in Hunter. To achieve this objective, three 15000 m³ per day NEWater plants need to be allocated in Port Stephens (2) and Dungog (1), amounting to a total CAPEX of 562 million AUD, which also includes the capital cost of additional wastewater pipeline connection. The proposed investment also incurs 11 million AUD annual operating costs and 54,000 tonnes of GHG emission. The jobs created to operate such facilities are 78 Full Time Equivalent (FTE) positions. Under the constraint of raw source water extraction, residential water demands, and industrial water demands, including those from energy sector, are all met accordingly with drinking water or non-drinking water (drinking water can be converted to non-drinking water in the model, but the reverse is forbidden). The model signals the investment of NEWater, but the actual capacity and location of investment are still subject to the possibility of extremely droughts across the region, practicability of pipeline construction, etc.

3.4 Liddell and Bayswater power plant decommission scenario

The Hunter's affluent coal storage and developed coal mining industry boost its economy and makes it the energy hub of the New South Wales (NSW) [55]. Four coal-fired power plants are located across the region, generating 8840 MW electricity and accounting for 44% power generation in NSW [39]. Nonetheless, SDG indicator 7.1 aims for sustainable energy security: "By 2036, ensure universal access to affordable, reliable and modern energy services" [56]. The NSW government has set an aspirational goal to achieve net-zero emissions by 2050 [57]. The local policies of the Hunter also echo this ambitious goal. The Hunter Regional Plan 2036 calls for the diversification of the energy sector to take advantage of "the region's potential to be a major hub for next-generation power". The regional government promises to promote initiatives that can combine economic and energy diversification, with two major coal-powered thermal power stations being scheduled to close in 2022 and 2035 (Liddell and Bayswater) [39]. The capacity of Liddell and Bayswater power plants is 2000 MW and 2640 MW respectively, amounting to 52% of the region's total power generation. With about 10% of the generated electricity used to supply local energy demand, 200 MW and 464 MW vacancy of energy need to be filled in 2022 and 2035 respectively. Since the model uses 5 years as interval from 2016 to 2036, 2022 and 2035 are rounded to 2021 and 2036 respectively to simulate the plummet in electricity supply. With a total of 13 types of green technologies assessed in the resource-technology network, the resilience.io platform can provide a high-level optimization of available options and signal the potential plan with minimized costs and GHG emission.

With investment on the presented matrix of technologies, the electricity demand of all citizens can be met at both 2021 and 2036 across the region. The accumulated CAPEX to achieve the objective is 4.52 billion AUD at 2021 and 10.8 billion AUD at 2036. The associated annual OPEX is 91.2 million AUD at 2021 and 218 million AUD at 2036. With proposed clean energy scheme, the GHG reduction that can be achieved from 2016 level is 22.7% at 2021 and 53.3% at 2036. Figure 8 shows the optimal energy structures provided by the model in both 2021 and 2036. It is evident that solar panels, combined cycle gas turbine with carbon capture and storage (CCGT-CCS) and onshore wind energy conversion systems are most recommended by the model, due to their relatively low GHG emissions or low costs. Small-scaled biofuel and hydro power plants accounts for 11.6% and 10.6% of total clean energy facilities, suggesting the feasibility of decentralized distribution for such technologies in various regions. In addition, a total of 784 FTE jobs are created to support the operation of invested facilities.

3.5 Waste-to-Energy (WtE) scenario

In this scenario, a high-level optimization of WtE technologies in 2036 is provided. The optimal strategies are evaluated in the context of business as usual scenario. Biosolid, municipal solid waste, agricultural waste and other organic waste within the study area are considered as (co-)feedstocks of renewable energy generation. Their spatial distribution lays the foundation of quantifying energy potential to be recovered from several WtE pathways [3]. A total of 19 combinations of technologies and feedstocks, including biochemical and thermochemical technologies (anaerobic digestion with thermal options and gasification) are modelled in the resource-technology network of resilience.io. Compared with traditional landfills, they are viewed as 'green' candidates to complete the WtE pathway. Table 3 also shows the details of evaluated technologies in terms of modelling inputs.

Both biogas and electricity are generated as the output resources of various anaerobic digestion (AD) technologies. Within the context of this study, the (co-)digestion of various feedstocks is evaluated. Thermal hydrolysis option (AD-THP) is also included in the model as promising extension of AD [41]. Both

syngas and electricity can be generated as the output of fluid-bed or plasma gasification technologies, which operates at high temperature above 750 °C to convert organic waste into syngas, comprising hydrogen, carbon monoxide and usually carbon dioxide. Syngas can be further upgraded through methanation process, where hydrogen reacts with carbon oxides to form methane and water [58]. Biogas and syngas can then undergo pressure adsorption swing purification for upgrading to natural gas quality [46]. Electricity and biogas/syngas generated are used to support energy network by feeding into either electricity or gas grid to fulfil corresponding demand (if any). In addition to the common centralized facilities, technologies with decentralized features are also incorporated in the model to evaluate the feasibility of both options in a systematic approach. Solid organic wastes are also allowed to be transported by truck from region to region, which opens up flexibility for centralized waste treatment by considering feedstocks as well as demands in a holistic way. The model simulation and optimization start from year 2016 where no WtE facility is installed. With 5-year intervals, the model progressively suggests optimal WtE strategies up to 2036 based on both economic incentives and spatial-temporal constraints. The results are presented for biosolids, municipal solid waste, agricultural waste and other organic waste. Note that agricultural waste and other organic waste (post-consumer food waste, etc.) are shown together as same technology data are used.

3.5.1 Biosolids

The diagrams below summarise the biosolids WtE facility treatment rate, energy production rate and number of installations by regions and types of technology. The transportation of biosolids is also included.

Four biosolids WtE options have been selected by the model at the timestamp of 2036. Plasma gasification with MSW as co-feedstocks (plasma), AD with thermal hydrolysis (AD-THP) and AD with MSW and wastewater as co-feedstocks (AD-co) are favoured by the model based on the objective function and defined economic and environmental performance indicators (see Supporting Information Part A Table A3). Pyrolysis and incineration of biosolids are eliminated by the model. The reason is presumed to be their inefficient conversion in generating renewable energy. 16.5 GWh per annum of energy can be generated from biosolids mainly in the form of natural gas, which amounts to 5.1 GWh of electricity. This can be used to reduce Hunter Water's wastewater treatment energy consumption by ~16%. Two centralized AD-THP are suggested by the model in Central Coast and Lake Macquarie respectively to treat biosolids only, accounting for ~70% of total biosolids in the study area. They are selected due to their relatively low costs. Plasma gasification are proposed to treat 8.6 tonnes per day biosolids together with municipal waste generated in or transported to Newcastle. The plasma plant is mainly used for municipal waste treatment, but the remaining capacity of the facility is further utilized for biosolids WtE processing. AD co-digestion of MSW with biosolids are also proposed in Port Stephens, Maitland and Cessnock. The plants treat most of the MSW in the corresponding region and handle a smaller portion of local biosolids. The remaining biosolids will be transported to Newcastle for centralized plasma gasification treatment. A farm AD plant is also allocated in Central Coast to recover energy from the remaining biosolids that will not be treated by the centralized AD-THP. This shows that the model only selects decentralized facilities when centralized plants cannot treat all the waste in a region.

3.5.2 Municipal solid waste

Similar to the biosolids results, pyrolysis and incineration are not selected by the model. Between two gasification options, plasma technology outperforms fluid-bed gasification for its lower cost per unit energy generation. The geographic centrality of Newcastle in the study area is recognised by the model. Two centralised gasification plants are planned in Newcastle, which treat most municipal waste from Newcastle, Maitland, Port Stephens and Lake Macquarie, accounting about 50% of MSW generated in the study area. Investing the high capacity facilities in Newcastle minimizes the transport costs of MSW from other regions. AD with municipal waste and liquid waste as co-feedstock (AD-co) is planned in Port Stephens, Maitland and Cessnock. No WtE facility is allocated for both Dungog and Branxton, whose MSW will be transported to Maitland or Port Stephens for treatment. Central Coast will be able to digest 124 tonnes per day of its own municipal waste in 2036 with AD-THP for MSW and decentralized farm AD. A small amount of waste is transported to Lake Macquarie to fill the remaining capacity. By processing biosolids and MSW, 178 GWh of biogas/electricity is produced, amounting to 55.2 GWh electricity. This can support about 60% of total electricity consumption by Hunter Water.

3.5.3 Agricultural and other organic waste

Agricultural and other organic waste feedstocks can contribute up to 80% of total WtE energy generated, as they are the largest source of feedstocks in the studied area. Decentralised digestion plant is most favoured by the model with no transportation across the regions. This is mainly due to the large quantity of agricultural available feedstocks, as well as the decentralized nature of agricultural waste distribution. Transportation becomes less cost-effective for large organic mass. A combined approximately 854 GWh energy can be generated and used by injecting into grid. 94% of the energy is in gas form and the rest is electricity.

In 2036, zones cannot reach 100% of WtE conversion due to excessive amount of organic feedstock identified in the region. Due to its relatively high waste generation, Central Coast treats only 28% under the spatial-temporal constraints included the model (land use, labour hour, etc). Newcastle and Cessnock are well above average due to the installed gasification and AD-THP facilities. The remaining regions recover about half amount of identified waste. The rest of the waste can only be landfilled or recycled by existing waste processors in the model, incurring potential energy debit and certain gate fees.

3.5.5 WtE performance indicators

This section presents various performance indicators for the model suggested WtE strategy at 2036, including CAPEX, OPEX, present values (PV), GHG emission, etc (Table 4). The potential landfill levy and gate fee savings for waste disposal are displayed from 2016 to 2036 in present values. The equivalent revenue of energy generated is also calculated to show the financial drivers behind the model results.

For biosolids treatments, slight GHG emission reduction is observed when compared with BAU scenarios. This is contributed by the reduced electricity consumption for background facilities (wastewater and water treatment, etc). Besides the economic and environmental indicators stated above, a total of 72 FTE jobs are required to operate the allocated biosolids WtE units. This reveals that WtE installations also support economic activity in the region by creating new jobs. Compared to business as usual scenario, a present value saving in the order of \$91m over 20 years can be achieved, which is the main driver of biosolids WtE optimization. The transportation and reuse of biosolids can also be avoided in a scale of \$33.2m, as biosolids are consumed in WtE facilities. Municipal solid waste present value figures reveal that the high landfill levy rate and high efficiency of renewable energy generation drive the model to optimize the MSW treatment as much as possible. For agricultural and other organic wastes, the generated energy, mainly presented in natural gas, can be very competitive to imported natural gas or electricity, which is the main driver of optimization.

3.6 Policy intervention scenarios

Decision makers face political challenges or encounter other key considerations that encourage or penalise certain technologies or resources. The economic and environmental sensitivity of WtE modelling should be evaluated. Carbon pricing scheme was introduced to Australian industrial sector from 2012 with a cost of \$23 per tonne of emitted carbon dioxide, which was abolished later in 2014 [59]. In this scenario, the carbon credit prices are set as alternatively \$25, \$75 or \$125 per tonne of CO₂ to study its effects on the three key indicators: CAPEX, OPEX and GHG emission (Figure 13). The increase in carbon price is achieved by increasing the weighting of GHG emission in the overall RTN optimization. The levels of prices are referred to as low, medium and high price respectively. The below CAPEX and OPEX figures only consider WtE technologies. GHG emission includes WtE, landfill and other energy generation sectors to demonstrate the impact of carbon price in the entire energy sector.

Based on the model, a higher carbon price can effectively accelerate the transition of energy structure towards a low-carbon direction. More WtE productions are favoured by the model considering that less electricity demand from power station reduces carbon emissions significantly. This results in different levels of increases in both CAPEX and OPEX under various carbon prices. Besides WtE technologies, higher carbon price also boosts the installation of renewable energy technologies such as solar panel, wind farm, hydroelectricity plant, etc. They substitute part of coal-fired power stations, but with much lower emissions. Under this scenario, a high carbon credit price (125 dollar) can thus reduce the carbon emission by about 21% in the entire system with 8.1% of increased capital cost.

Feed-in tariff (FIT) is another common policy intervention in energy sector. Similar to carbon price, FIT was once introduced by New South Wales government in 2009 at \$0.60 per kWh and revoked in 2011 [60]. In this scenario, FIT of 60 cents per kWh for electricity and \$0.20 per kWh for gas are applied. The different tariffs for electricity and gas are designed to account for the conversion efficiency from electricity to gas as well as the cleaning process of biogas to qualified natural gas.

CAPEX of WtE will increase by 16.3% due to the increased installation. Operating cost of WtE will be significantly reduced after accounting for the FIT. The carbon emission in the entire system will also decrease by about 20% due to the larger role played by both renewable energy and WtE facilities. Overall, the adoption of both carbon credit price and FIT are indicated as effective means to accelerate the transition of energy structure for reducing GHG emissions. Other considerations, such as public support, should also be accounted for decision makers to decide to implement interventions with encouragement or penalization.

Conclusions

An investigative systematic modelling approach of studying FEW2 nexus in the Hunter Region, under the assumptions presented, leads to the initial findings presented above. As a summary, the holistic approach supported by resilience.io proved to be insightful in decision-making process for water, energy and waste sectors in the context of FEW2. The feasibility of agent-based modelling and MILP optimization model has also been further demonstrated, as the demand and resource flow supply are successfully simulated for the combined benefits of economy and environment in the context of Hunter Region.

Water reclamation technology, NEWater, is considered as the best candidate to mitigate extremely drought periods across the Hunter. About 35% of wastewater need to be recycled for raw water production in order to avoid the water storage level from falling below level 1 restriction. To accommodate the decommission of Liddell and Bayswater power plant, solar panels, CCGT-CCS and onshore wind energy conversion are most recommended due to relatively low costs or emissions. Through WtE pathway, a total of 854 GWh per annum renewable energy can be generated in 2036 and 94% of the generation from waste is in the form of biogas or syngas. By upgrading to natural gas and injecting into gas grid, the gas-to-electricity conversion loss can be avoided, and less energy transmission loss will incur. Biogas generation is thus considered to render more economic benefits than electricity. Two commonly adopted policy interventions—carbon credit price and feed-in tariff—are investigated to demonstrate their economic and environmental effect. Both policies will encourage the installation of WtE technologies when applied, which also leads to reduction in GHG emission due to reduction in coal-fired electricity generation.

As the government of NSW has been elaborating the Hunter Regional Plan 2036 to further deliver prosperity for the region in a long term, the system approach has shown great benefits for decision makers through our local dissemination events [61]. Modelling work at this stage was still investigative. The model was used to establish and demonstrate the merits of a digitally-driven systems approach and was not designed to support planning decision or investment case.

As a next step, a stakeholder-oriented system model development—in particular on model validation and database development with wider coverage of promising technology options—will enable more robust modelling outputs to be generated. These outputs allow better informed investment and policy decisions, taking into account a wider range of opportunities, for which this paper is only a starting point. For example, the population model can be used to track existing skills and align education with future skill needs, something that we know is critical to the regional strategy and could be linked to the creation of local jobs and an attractive economic environment when evaluating different technical and policy options. Moreover, there is an opportunity to bring health metrics into the resilience.io platform, which could be used to build the economic case to invest in improving air quality in the region. The systems approach can then be seen as a starting point for the exploration of different visions and futures, with local stakeholders at the centre of the decision-making process. The data as well as simulated scenarios, will enable well-informed decisions and further detailed examination of options deemed attractive at the systems level. Following a systems approach, the interdependencies between infrastructure systems and sectors will continue to be at the core of planning integrated solutions at the national, regional and local level.

Abbreviations

<i>Abbreviation</i>	<i>Definition</i>
ABM	Agent-based model
AD	Anaerobic Digestion
AD co	Anaerobic Digestion with municipal waste and liquid waste as co-feedstock
AD with THP	Anaerobic Digestion with Thermal Hydrolysis Pre-processing
AUD	Australian Dollar
BAU	Business as usual
CAPEX	Capital Expenditure
CCGT-CCS	Combined cycle gas turbine with carbon capture and storage
EFW	Energy-Water-Food Nexus
FEW2	Food-Energy-Water-Waste Nexus
FIT	Feed-in tariff
FTE	Full Time Equivalent
GAMA	Greater Accra Metropolitan Area
GHD	GHD Group Pty Ltd
GHG	Greenhouse Gas
GLPK	GUN Linear Programming Kit
HW	Hunter Water
MILP	Mixed-Integer Linear Programming
MSW	Municipal solid waste
NSW	New South Wales
OPEX	Operating Expenditure
plasma	Plasma Gasification
PSA	Pressure Swing Adsorption
PUB	Public Utilities Board
PV	Present value
RTN	Resource technology network
tpa	tonnes per annum
UES	Urban Energy System
UWOT	Urban Water Optioneering Tool
WtE	Waste to Energy
wtp	Waste Treatment Plant
wwtw	Wastewater Treatment Work

Declarations

Availability of data and materials

All data generated or analysed during this study are included in this article or the supporting information attached with this article, except for part of Hunter Water Corporation data which are private and confidential.

Competing interest

The authors declare that they have no competing interests.

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Author's contributions

B. Feng implemented the mathematical models, generated the computational results, and prepared the paper. K. H van Dam, X. Wang and M. Guo developed the tools, and designed the analysis. S. Passmore designed the project and collected the data. N. Shah, and X. Wang supervised the work. All authors have contributed to the paper writing and given the approval to the final version of the manuscript.

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Tables

Table 1. Feedstock gate fee or landfill price (AUD 2016).

MSW - Landfill	78.20
Forestry	78.20
C&I / C&D	135.70
Post-consumer food waste	78.20
Manure	25
Other organic wastes	10

Table 2. BAU performance indicators in year 2036.

CAPEX	OPEX	Present Value of Cost (7% discount rate over 20 years)	GHG Emission
228 million AUD	38 million AUD per annum	370 million AUD	145,400 tonnes per annum

Table 3. Waste treatment and recovery technologies in modelling.

Technology Category	Waste Streams (Input)
Large AD with THP	Biosolids
	MSW
	Agricultural and other waste
Large AD	Biosolids
	MSW
	Agricultural and other waste
Farm AD	Biosolids
	MSW
	Agricultural and other waste
Large AD co	MSW
	Biosolids
Plasma gasification	Biosolids
	MSW
	Agricultural and other waste
Fluid-bed gasification	Biosolids
	MSW
	Agricultural and other waste
Incineration	
Pyrolysis	

Table 4. Summary and comparison of the BAU scenario with other scenarios in Section 3.5

	CAPEX (million AUD)	OPEX (million AUD per annum)	Cost PV (million AUD)	Compared to BAU (NPV in million AUD)	
				Reduction in OPEX	Energy cost reduction
BAU	228	38	370	-	-
Biosolids	150	6.6	279	33.2 (management cost)	9.22
MSW	136	5.6	98.3	28.3 (landfill levy)	89.8
Agricultural et al	258	10.7	173	44.4 (landfill or gate fee)	146

* Both CAPEX and OPEX are included for cost present value. The cost avoided and equivalent revenue of generated energy are not included in the present value of cost.

Figures

Figure 1

The intertwined relationship amongst food, energy, water and waste [3].

Figure 2

The scenarios to be explored in this study.

Figure 3

Multiple layers included in the model [47].

Figure 4

Example pathways for processing and use of waste and WtE pathways [3, 48].

Figure 5

GHG emission (tonnes per year) for business as usual scenario.

Figure 6

Hunter Water Storage and Outlook from July 2017 to July 2019 [52].

Figure 7

NEWater Production Rate (a) and Recycle Water to Wastewater ratio (b) vs time.

Figure 8

Model-suggested optimal energy structure in 2021 (a) and 2036 (b) (by energy generation capacity).

Figure 9

Results of biosolids: (a) Biosolids Treatment Rate in 2036 (tonnes per year). (b) Biosolids WtE energy generation in 2036 (Total: 16.5 GWh). (c) Number of biosolids WtE facility Installation by district in 2036. (d) Number of biosolids WtE facility Installation as time progresses.

Figure 10

Results of municipal solid waste: (a) MSW Treatment Rate in 2036 (tonnes per year). (b) MSW WtE energy generation in 2036 (Total: 162 GWh) (c) Number of MSW WtE facility Installation in 2036. (d) Transportation of MSW per district (tonnes per day).

Figure 11

Results of agricultural and other organic waste: (a) Treatment rate (tonnes per year) in 2036. (b) WtE energy generation in 2036 (Total: 676 GWh). (c) Number of Installation by district in 2036. (d) Number of Installation as year progresses.

Figure 12

WtE development that can be achieved in 2036.

Figure 13

Economic and environmental performance with different carbon prices.

Figure 14

Change in the three key indicators after applying FIT.

Supplementary Files

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- [SIFoodEnergyWaterWastenexus.docx](#)