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Regional Power Plan Assessment Accounting for Environmental Footprints

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Enabling a higher share of renewables in power planning at the municipal and regional scale is essential for offering local communities a path to sustainable development. However, the utilisation of renewables also carries certain environmental burdens which have to be accounted for in the process of system design and planning. The current paper takes this issue as a departure point, adding the electrical energy storage as a degree of freedom and its influence on the environmental footprints – represented by Greenhouse Gas and Water Footprints. The proposed model and the illustration case study clearly demonstrate the strong dependence of the footprints on the size of the storage facility. Future work should extend the model to account for all essential problem features – including a longer planning horizon, additional footprints and their inter-relationships, as well as the interaction with the economic performance of the system.

1. Introduction

For minimising the footprints of industrial, and other activities, the use of renewables (Ellabban et al., 2014) is a primary measure, alongside the reduction of energy demands. For the integration of renewables into energy systems, the degrees of freedom have to be optimised (Čuček et al., 2012), accounting for the trade-offs of the competing trends. The increased use of biomass for energy (Lam et al., 2010) may reduce Greenhouse Gas (GHG) Footprints for shorter transportation distances. Larger harvesting areas overturn this trend, and GHG savings are compensated by increased use of fossil fuels for transportation. Other renewable energy sources can be harvested, exhibiting benefits and drawbacks that need balancing from the Life Cycle perspective (Ludin et al., 2018). For instance – for wind and photovoltaic (PV) generators (Nugent and Sovacool, 2014), oversizing may lead to unproductive investments, land diversion (Gorayeb et al., 2018) from food production, and potential to energy waste. This makes optimal design necessary (Mohammad Rozali et al., 2014).
A vital degree of freedom is energy storage (Nasrolahpour et al., 2016) – batteries (Radu et al., 2017) or power-to-fuel hubs (Koytsoumpa et al., 2016). A flexibility evaluation methodology for power planning is proposed in Lu et al. (2018). The paper demonstrates quantitatively the relationship between ensuring the flexibility of the system and its capability to maximise the utilisation of renewable energy sources.
The application of Process Integration to power system planning has been pioneered by Wan Alwi et al. (2012), who developed a targeting model for minimum power import to industrial sites, considering energy storage. Power import or retrieval from storage is used for the start-up, followed by operation in a self-sufficient mode for a single day, and then storage or export any excess power at the end. That initial model neglected conversion losses. The concept has been in continuous development – a, as can be seen from the recent application to renewables generation backed up by diesel engines (Tay et al., 2020).
A MILP method for power flow planning has been presented in Theo et al. (2016). The model performs profit maximisation using a linearised modification of the Net-Present Value. Based on a case study, the electricity load profiles have been analysed, accounting for AC and DC electricity flows. The decision variables model the

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storage technologies selection and capacities, the generation schedules, power storage and retrieval. The model stops short of evaluating the environmental footprints, which leaves scope for extending the research.
A storage planning tool (Haas et al., 2018) has been proposed for 100 % renewable power systems based on wind and photovoltaic generation. The evaluation includes batteries, pumped hydro, and hydrogen power storage. The optimisation minimised the total system cost, but environmental footprints are not modelled.
The influence of load shifting on the need for power storage was investigated in (Mohammad Rozali et al., 2018). The method develops heuristics for finding the minimum storage size. First, the normal Power Pinch procedure is applied. Based on that, the method performs economic analysis of the load shifting options, and the case study shows that economically justifiable load shift can lead to a 30 % reduction in the storage size. The consideration is entirely from the viewpoint of power generation and distribution. However, to enable such load shifting, extended inventories of materials are needed on the demand-side, plus additional operating procedures. Such demand-side issues are not discussed in this paper. An open-source software platform Switch 2.0, for planning transitions to low-emission electric power systems, is presented in (Johnston et al., 2019). It enables evaluation of economic features, power generation and storage and investment planning. This project is still in intensive development, not yet offering emission evaluation features or appropriate visualisation.
An application-focused literature review has been presented by Ahmed and Khalid (2019) on the role of forecasting models in renewable power system planning and operation. It includes a section on power system sizing – focusing on energy storage. The covered references deal mostly with the optimisation of operating and investment costs. A long-term multi-regional power system planning model is proposed (Li et al., 2020) with monthly, regional and sectorial demand forecast and optimisation of installed capacity, power grids and storage facilities. Scenario analysis is conducted to address policy uncertainties of the carbon tax and power substitution. The study focuses on macro-region modelling and CO_2 emissions, leaving out the potential emissions from transportation and the use of renewables, as well as the life-cycle scope.
Building upon the Power Pinch method (Mohammad Rozali et al., 2014), for small regional systems, the current work adds extensions for power inventory planning (Golari et al., 2016) for a regional system on the example of a municipality. The problem has specifications for power demands varying in time, PV and wind harvesting capacities (Akram et al., 2017), and storage capacities (Berahmandpour et al., 2019). The procedure takes as further inputs the specific footprints of the energy sources – renewables and the grid. The central power grid and the installed storage are used as degrees of freedom for clearing the temporary deficits or excesses. The model maximises the use of renewables and evaluates the GHG and Water Footprints (WFP) as a function of the electricity storage size, obtaining targets for the storage to minimise the cumulative footprints.

2. Model extension to account for environmental footprints

The current model is an extension of the fundamental Power Pinch model, accounting for environmental footprints on a Life Cycle basis. The model is applied to a municipal-scale system (Figure 1). The system is assumed to have at its disposal a battery as storage. It is assumed that the footprint factors for GHG and WFP of the renewable generation are lower than those associated with the grid power. This leads to the objectives to maximise the utilisation of the renewable capacity and to minimise the power import from the grid.
Power export has no effect on the footprints of the municipal system. It may have an influence on the revenues and on global emissions. Export is not considered in the current work but will be included in a future model.
The model constructs the power flow - time cascade using time slices and a modelling horizon of 1 h and 24 h. The battery storage is assumed to have specified, constant values of the charging and discharging efficiencies.

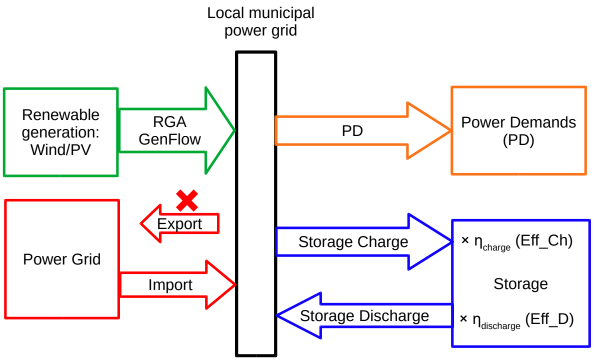


Figure 1: The modelled system. RGA: Renewable Generation Availability; GenFlow: local power generation from renewable sources; PD: Power demands; CSL: current storage level. SCap: storage capacity

The power supply flows for fulfilling the demands or charging the storage should be arranged the following priority: (1) renewables generation; (2) storage discharge; (3) grid import. Within each time slice, the following power management policy is applied.

1. Power can be delivered to the demands or to the storage facility
2. The first priority of the system is to serve the power demand - this is its main function.
3. Only eventual surplus from the generation, after satisfying the demands can be stored in the battery.
4. Any grid import should take place only in the case when the sum of renewables generation and storage discharge still leave a deficit. It is assumed that power import is always available as much as necessary.

For each time slice TS, the following equations are applied – assuming MS-Excel syntax (Excel, 2020):

Availability Balance	$BalA[TS] = RGA[TS] - PD[TS]$	(1)
Generation Excess (Binary/Boolean)	$GEx[TS] = IF(BalA[TS] > 0{,}1{,}0)$	(2)
Generation Deficit (Binary/Boolean)	$GDf[TS] = 1 - GEx[TS]$	(3)
Excess availability of renewables	$Excess[TS] = MAX(BalA[TS], 0)$: filter the negative values	(4)
Deficit 1 (after attempting renewable)	$Deficit\_1[TS] = MAX(-BalA[TS], 0)$	(5)
Scope of power retrieval from the storage (case of deficit)	$RScope[TS] = CSL[TS-1] * Eff\_D$	(6)
Power retrieval from the storage	$SD[TS] = MIN(Deficit\_1[TS], RScope[TS])$	(7)
Scope for power storage (excess)	$StorScope[TS] = (StorCap - CSL[TS-1])/Eff\_Ch$	(8)
Storage charging	$SCh[TS] = MIN(Excess[TS], StorScope[TS])$	(9)
Generation from renewables (up to the availability)	$GenFlow[TS] = IF(BalA[TS] > 0, PD[TS] + SCh[TS], RGA[TS])$	(10)
Deficit 2 (deficit after storage use)	$Deficit\_2[TS] = Deficit\_1[TS] - SD[TS]$	(11)
Import from the grid	$Import[TS] = MAX\left(Deficit_{2[TS]}, 0\right)$	(12)
Update of the storage level	$CSL[TS] = CSL[TS-1] + SCh[TS] * Eff_{Ch} - SD[TS]/Eff\_D$	(13)

The model ensures that for every time slice, the power demands are served, and the inventory in the storage takes feasible values. After the power-time cascade is completed, the GHG and WFP associated with the operation profile are estimated. Eq(14) includes the GHG emissions of renewables generation, power grid import and power storage system, based on a life-cycle weighted emission factor per electricity retrieved from the storage (Rapier, 2020). The WFP of power storage can vary widely – from the insignificant 11 kg water/kg battery weight (Tytgat et al., 2018), up to 200 m^3/MWh (Bakken et al., 2017) for pumped hydro storage, so the storage term in Eq(15) – $WFP_{storage}$, has to be estimated for each specific technology.

$$GHG(Slice)\ [kg\ CO_2] = GHG_{renewables} + GHG_{grid\ import} + GHG_{storage} \tag{14}$$

$$WFP(Slice)[m^3\ Water] = WFP_{renewables} + WFP_{grid\ import} + WFP_{storage} \tag{15}$$

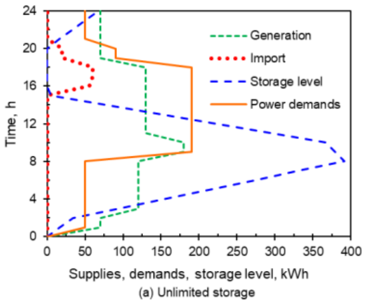
3. Case study of regional power targeting/planning including environmental footprints

In this section, the developed model is applied to a case study, adapted from Mohammad Rozali et al. (2013). The specification represents the daily demands with five hypothetical appliances (Theo et al., 2016), as shown in Table 1. The parameters of the power sources are listed in the second part of Table 1. The charging efficiency of the energy storage system is 85 %. The discharging efficiency of the energy storage system is 83 %.

Table 1: Profiles of the power demands and renewable power generation availability

Power demand	Time, h	Power rating, kW	Power consumed, kWh
Demands			
Appliance 1	0 - 24	30	720
Appliance 2	8 - 18	50	500
Appliance 3	0 - 24	20	480
Appliance 4	8 - 18	50	500
Appliance 5	8 - 20	40	480
Renewable power generation availability			
Solar photovoltaic (PV)	8 - 18	60	600
Wind	2 - 10	50	400
Biomass	0 - 24	70	1,680

The model is applied first in an unconstrained mode – specifying the storage size as 1,000 kWh and then a sensitivity study was performed gradually reducing the size to 0 kWh. The power cascade is plotted in Figure 2, showing two points of the evaluation. For the unconstrained storage, the local generation completely utilises the renewables. This results in 215.5 kWh power import. For the storage limit of 50 kWh, the local generation is about half of the availability. This results in cumulative power import from the grid of 498.5 kWh. The environmental footprints for the various storage capacity limits were evaluated using Eq(14) and Eq(15). The footprint factors of GHG and WFP over the Life Cycle are shown in Table 2. These values are weighted and expressed per unit of delivered power – generation for the renewables, imported power, and storage discharge.



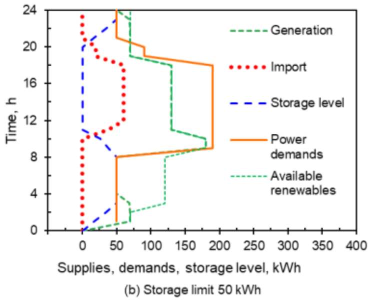
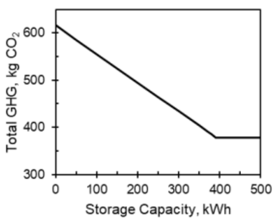


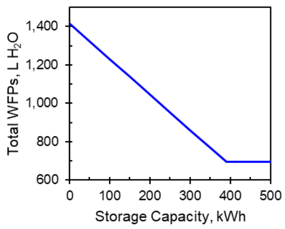
Figure 2: Power balance over time

Table 2: Life Cycle GHG Emission factors of Power Generation methods

Power source	GHG, g CO_2/kWh	WFP, L H_2O/kWh	Data Source
Solar	85	0.33	GHG data (WNA, 2011)
Wind	26	0.043	WFP data (Jin et al., 2019)
Biomass	45	85.1	Storage GHG data (Rapier, 2020)
Power grid (coal)	888	2.22	
Storage (battery)	70	0	



(a) GHG Emissions



(b) Water Footprints

Figure 3: Variation of the daily cumulative GHG and WFP with the installed storage capacity

The variation of the GHG and WFP footprints is shown in Figure 3. The trends demonstrate a quantitatively significant dependence on the battery storage limit. For the 24 h cycle, the GHG footprint varies from 347 kg

CO_2 for unlimited storage, up to 617 kg CO_2 for disabled storage, constituting 78 % increase. The WFP variation for the same cases is from 694 L to 1,414 L (104 %). In Figure 3a, the total GHG emissions decrease with the increase of storage capacity and remain unchanged after the storage exceeds 391 kWh. This is because all surplus power generated from renewables can be stored. When the storage capacity is further decreased, the excess renewable generation cannot be completely stored, resulting in incomplete utilisation of the availability. This causes the import of power from the grid to increase. When the storage capacity drops to zero (no storage), the total import from the power grid is maximum. This corresponds to the maximum footprints of the system.

The relationship between WFPs and different storage capacity is shown in Figure 3b. The trend is similar. Figure 3b shows that the GHG emissions and water footprint remains constant when the installed storage capacity is more than (>391 kWh) the required capacity. There is an assumption underlying the calculation. The accounting of environmental footprints of a battery or storage is challenging as it cannot be physically measured in the usage phase. The conversion factor is obtained by dividing the absolute embedded footprint value by a functional unit (per kWh), considering the lifetime of the battery under an ideal condition. The overall Life Cycle footprint should be distributed over the battery charge and discharge cycles. The GHG and water footprint after >391 kWh is expected to show an increasing trend in a degree less significant than the increment at installed storage capacity < 391 kWh. However, the strong dependence of the footprints on the size of the storage facility as identified in this study is still valid, as supported by Rapier et al. (2020). This leads to the outcome that the sustainability of renewable energy is highly dependent on the storage parameters.

4. Conclusions

This contribution introduces the simultaneous evaluation of the environmental footprints for power generation from renewables, power grid import and storage in the context of municipal power planning. It has been shown that the dependence of the footprints on the storage size is quantitatively significant – with variations of up to 78 - 100 % compared with the unconstrained storage, and have to be accounted for in the future evaluations.

The future work should extend the model to include a longer operation horizon, accounting for possible demand increases and uncertainty. Regarding the model completeness, the planning model of (Theo et al., 2016), which contains the key options for the system choices, should also be complemented with the consideration of Nitrogen Footprints alongside the GHG and WFP, while should account for the possibility of power export from the site, as an additional degree of freedom. Considering the wider pool of storage options would also bring about a wider variation in the WFP factors. For example, pumped hydro storage is associated with significant evaporation losses. It is also important to set up a differentiated specification for the footprints resulting from the operation phase and other phases of the Life Cycle since this would bring the model closer to the real practice and increase its fidelity. The extension should also include the economic aspects – accounting for the usual economic costs, as well as for the footprints, applying the concepts of eco-cost, eco-profit and sustainability profit. An interesting direction is also the use of surplus electricity for producing chemicals – including from CO_2, following the e-Refinery (TU Delft, 2020) initiative.

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