Improving the Degree of Autarky of a 16 House Neighbourhood in the Netherlands - A case study

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***Abstract*—In this work we investigate the possibility to operate an existing neighbourhood in the Netherlands in a "*soft-islanded*" (near autarkic) way. For this, a multi-energy system, including optimal control, is modelled using PV panels, a combined heat and power generator and 6 kWh of battery storage per household. By utilizing the synergies between electricity, heat and bio-gas, the system provides a good solution to relieve stress on electricity grids within the context of the energy transition. Simulation studies show that the envisioned system, with control, is able to reach a Degree of Autarky of 91% for the energy consumption.**

***Index Terms*—Micro-grids, energy management, optimization, multi-energy systems**

I. Introduction

With a drastic, country-wide reduction in the emission of CO_2 as the main goal, the *Energy Transition* is an ongoing effort to structurally reduce the use of fossil fuels by using renewable energy sources in the Netherlands [1]. Dominant in this transition is the goal to reduce the dependence on natural gas, which is the primary energy source for space heating, hot tap water and cooking in the Netherlands [2]. However, simply switching to all-electric cooking and heating is not feasible as the electrical grid in the Netherlands is not designed for such loads [3].

A possible solution to this problem is to reduce the possible strain on the electricity infrastructure by matching local generation and demand using intelligent control and optimization, such as presented in e.g. [4]. In extreme, we can completely avoid stress on the electricity grid if a group of households can be disconnected from the grid [5] and operated as an islanded micro-grid. However, creating such an islanded micro-grid can be expensive and is in general not strictly required as an energy infrastructure is already available. Instead, a group of households may be operated *soft-islanded*, meaning that there is still a connection to the main grid for stabilization, but the majority of energy is shared locally. The objective of such a soft-islanded grid is to maximize the *Degree of Autarky* (DoA) which expresses the share of locally produced energy in the total demand of energy. The DoA is defined as the percentage of energy consumption ($E_{\text{consumption}}$) from local sources [6], i.e.

$$\text{DoA} = \frac{E_{\text{consumption}} - E_{\text{import}}}{E_{\text{consumption}}} \times 100\%,$$

where E_{import} is the total amount of imported energy.

Such a soft-islanded microgrid is not limited to the control of electricity, however. Synergies between multiple energy carriers, such as electricity and heat, can be utilized to improve the overall system efficiency. Mancarella [7] has surveyed concepts and models for such integrated *multi-energy systems* (MES). Furthermore, the potentially possible configurations heavily depend on the local conditions and climate, see e.g. [8], [9].

For the climate conditions in the Netherlands, with mild winters, combining photo-voltaics (PV) with a Combined Heat and Power (CHP) unit proves to be a potentially complementary energy generation mix to deliver the required electricity throughout the year for such soft-islanded operation. In previous work, [10], we demonstrated that it is possible to drastically reduce the electricity imports from the grid with such a system if it is combined with small scale storage and optimal control.

This paper presents a feasibility study to soft-island an existing neighbourhood, consisting of 16 houses, in the Dutch town Markluiden with the aforementioned system design as presented in [10]. The fuel of the CHP is considered to be bio-gas, which can be produced from sources in the direct vicinity of the town (e.g. farms). The simulation studies are carried out using the DEMKit software [11] developed at the University of Twente. This tool allows to model a MES on the level of individual devices. Furthermore, different optimization algorithms are implemented in DEMKit to simulate the soft-islanding operation. More specifically, we use Profile Steering [12] as optimization framework, coupled with a double-sided auction for operational control [13].

Characteristics of the considered neighbourhood, together with reasons why this location is potentially suitable for soft-islanding operation, are discussed in Section II. The process to size the various components within the hybrid-energy system to perform soft-islanding is presented in Section III. The sizing is followed by results of a simulation study of a complete year, to obtain the DoA for this configuration in Section IV. Lastly, conclusions are presented in Section V. Additional details on Markluiden and an expanded case study are presented in [14].

II. Characteristics of the Neighbourhood

In Figure 1 a layout of the neighbourhood is given. The neighbourhood consists of 16 fully detached houses, which are all different. The residents are open to share data about their energy usage and schedules, and are willing to share their locally generated energy with their neighbours. Moreover, the residents filled out questionnaires to provide us with the information required for this case study.

Most of the houses were built several decades ago, with little to moderate insulation. The average heat resistance (R_c) is 1.3 K/kW, with 0.5 K/kW as the lowest value. There are two exceptions, which are very well insulated houses, built recently, where in the best case the R_c is 4.1 K/kW.

Only one of the houses makes use of renewable energy technology; it is outfitted with 12 PV panels and 2 PVT panels. (Note, that the PVT panels are not taken into account due to

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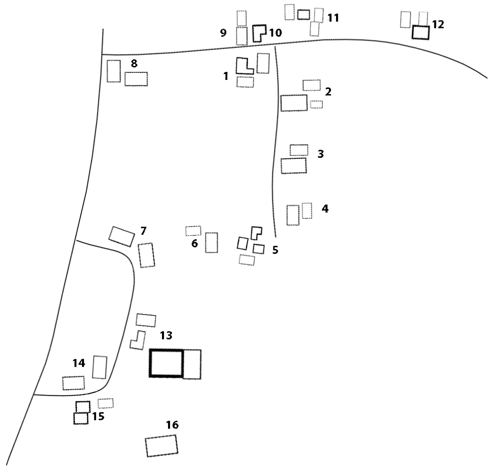


Fig. 1. Layout of the 16 house neighbourhood in Markluiden.

missing models and limited impact of 2 PVT panels on the neighbourhood scale) In total 11 of the 16 houses are suitable for the installation of PV panels. The remaining houses have a thatched roof (i.e. made of straw), which makes installation of PV panels impossible. For these houses it is assumed that PV panels will be installed elsewhere on the property (i.e on a shed or annex).

In most of the houses, the heat is generated by a traditional high-efficiency gas boiler and delivered to the indoor area using high-temperature radiators. Additionally, 7 houses use floor heating for the living room. In only one of the houses floor heating is used as the only means of heating.

The orientation of the houses is mixed, with seven houses East-West oriented and the remaining nine South-North oriented. The window area of the houses is specified based on standardized values depending on the year of construction and type of house [15]. This total area is then divided over all four sides of the building, whereby the given position of the houses in an online map is taken into account. On average the houses have a window area of 31 m^2, divided in 4.5 m^2 facing north, 8 m^2 facing west, 7.8 m^2 facing east and 10.6 m^2 facing south.

III. Sizing the Equipment

In this section we determine the proper size of the energy generating and storage devices (CHP unit, PV panels, battery) needed for reaching a scenario where the neighbourhood can be self-supplying for a large part of the year. As input for this we need the energy demand of the houses. We use the APLG to generate these profiles [16]. This ALPG needs specific characteristics, like family composition and work schedule, as input to generate a time series of power and heat consumption for the whole year. We take these characteristics from the available information of the neighbourhood and the questionnaires. This forms the base model, to which we add technologies that enable soft-islanding, and size them accordingly. A primary constraint here is that the comfort of connected customers may not be violated, e.g. they need to be supplied with the heat and electricity they demand. This sizing process is executed in three steps (details of which are given later):

- Firstly, the CHP is sized to fulfil both the heat and electricity demand during the colder months.
- Secondly, as the CHP already provides enough electricity during the colder months, the number of PV panels is determined to ensure that enough electricity is generated during the warmer and sunnier months, where the CHP does not provide enough electricity.
- Thirdly, the battery storage is sized to match supply and demand of electricity throughout the day by shifting energy in time, e.g. shifting electricity produced by PV to the evening, thus reducing both the electricity demand from, and supply to the grid.

For the sizing we do not consider the whole year but three weeks with varying properties. Week A in the summer, week B in the winter and week C in the autumn; details are given in Table I. The weather data used in this work was obtained from [17]. The control actions of the added technologies are optimized using the Profile Steering algorithm [12] and simulated using DEMKit [11].

TABLE I
Description of the test weeks.

Week	Date	PV generation	Heat demand
A	30 Jul. - 5 Aug.	very high	very low
B	22 - 28 Jan.	low	very high
C	15 - 21 Oct.	low	low

A. The CHP unit

The only source for heating and hot tap water is the CHP unit shared by all houses. As the comfort of the residents is the most important constraint, the capacity of the CHP unit must be large enough to satisfy the heat demand of all houses in the coldest week of the year (i.e. week B)*. The setpoint selected to trigger the heating device during the day is 18.0°C. Furthermore, the minimum allowed temperature in the house during night hours (between 23:00 and 8:00) is 14.0°C. In Figure 2, the average room temperature in week B for different CHP unit capacities (from 100kW_{th} to 250kW_{th}) is given.

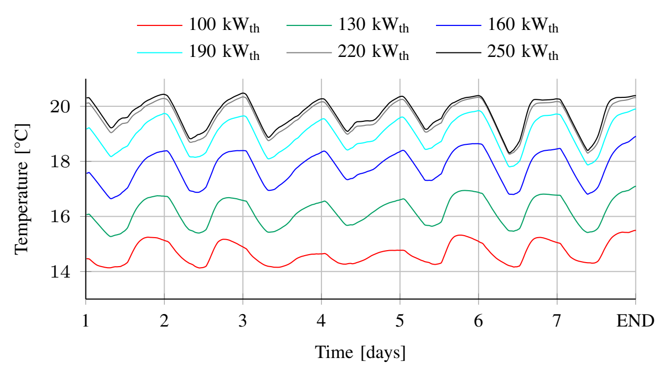


Fig. 2. Average zone temperature in week B for varied CHP sizes.

From Figure 2 it is clear that CHP units with a capacity above 190 kW_{th} can guarantee the thermal comfort inside the houses. However, investigation of individual temperature profiles of each household shows that a CHP capacity of 190 kW_{th} does not guarantee thermal comfort to some houses

*Note that it would also be prudent to improve the thermal insulation wherever possible, however, this has not been taken into account in this study.

(which are less insulated). A CHP unit with 250 kW_{th} power output is the minimum capacity that can ensure thermal comfort in all the houses of the micro-grid, and hence this size is selected.

Note, that electricity is produced by the CHP as a by-product from the heat-generation. The rest of the electricity demand should be provided by the PV panels and the batteries. Possible overproduction of electricity can be stored locally or fed back to the main grid.

For the CHP a heat / electricity production ratio of 2.25 is assumed. Instead of a normal heat buffer the neighbourhood makes use of a *aquifer thermal energy storage* (ATES) system as heat storage for the CHP. Hence, the sizing of a thermal buffer as considered in [10] is not necessary in this case.

B. The ATES system

ATES technology takes advantage of underground water deposits as medium to store heat over a long period. Hence, ATES could provide the neighbourhood with inter-seasonal heat storage, adding flexibility by matching the heat demand in colder periods to the heat (over)production in warmer periods. Using this system in the neighbourhood is requested by the residents, however, the feasibility of using an ATES system in the neighbourhood, and the sizing of that system are beyond the scope of this work. Both issues are addressed in [14]. The ATES system taken into account has a capacity of 5 MWh_{th}.

C. The PV panels

The sizing of the required PV panel area is done based on an analysis of *week A*. This is the warmest week in which the CHP will produce the least electricity and thus the micro-grid depends mainly on the production from the PV panels. For the PV panels a 19% efficiency is considered, as these are already used in the neighbourhood. Furthermore, the PV panels are assumed to be installed facing south wherever possible, and equally divided towards east and west in all other cases. The considered total surfaces of PV panels per household vary from 8 m^2 to 24 m^2. Lastly, in this determination a battery of sufficient capacity (13.5 kWh) per household is used to avoid capacity limitations in shifting energy from day to night. Note that the optimization of the battery size itself will be considered in the next subsection, where trade-offs between autarky and costs are made.

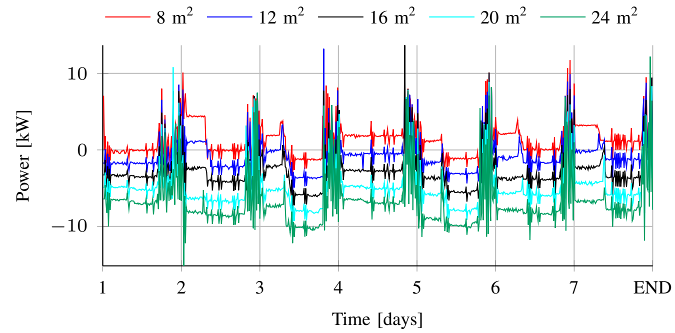
Figure 3a shows the optimized electricity usage of the whole micro-grid given the different values for the PV panel area, while Figure 3b shows the resulting SoC of the battery. From Figure 3a it is clear that even for the highest PV installation (24 m^2), some electricity is still imported from the grid, mostly at night. Figure 5a gives the amount of electricity imported from the grid depending on the PV panel area during week A. It is clear that the benefits beyond 16 m^2 of PV panels per household is very limited. Hence, again taking into account the cost of PV panels, a PV panel area of 16 m^2 per house is selected.

D. The batteries

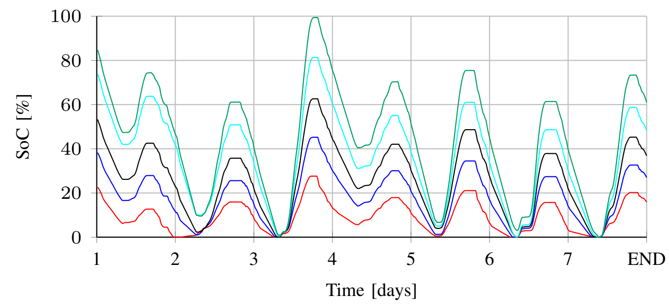
The sizing of the capacity of the electrical storage is based on an analysis of *week A*. For this analysis battery capacities of 3, 4, 5, 6, 7, 9, 11 and 13.5[†] kWh are considered. In Figure 4 the electricity import and export of the micro-grid and the state-of-charge (SoC) of the batteries are given.

From Figure 4a, it is clear that the total import from the grid decrease when the battery capacity is increased. Figure 5b shows the amount of electricity import during week A given the different battery sizes. With a total battery capacity of 3 kWh per household (48 kWh in total), almost 135 kWh of electricity is still imported from the grid. By increasing the battery capacity to 6 kWh per household the import is reduced to just over 62 kWh. However, beyond this 6 kWh per household, the improvement is only marginal. Moreover, we observe that the full capacity of a battery of more than 6 kWh is never fully utilised, i.e. the SoC never reaches 100 % (see Figure 4b) implying that the PV panels do not produce sufficient energy to supply the complete demand. So increasing the battery capacity any further does not yield improvements and thus a battery of 6 kWh per household is selected.

[†]13.5 kWh corresponds to a *Tesla Powerwall 2* battery, this specific battery is taken into account on the request of the Markluiden residents.



(a) Electricity usage.



(b) SoC batteries.

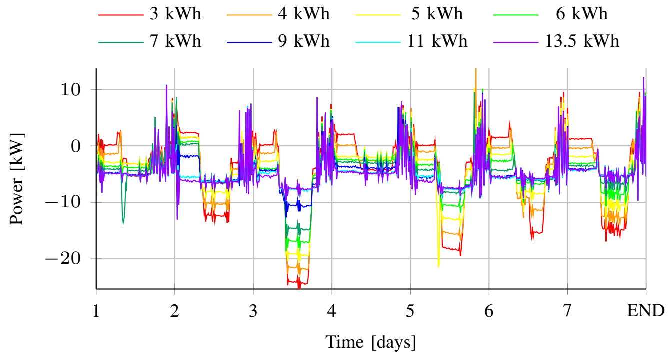
Fig. 3. Electricity usage and battery SoC in week A for varied PV areas

TABLE II
SUMMARY OF EQUIPMENT SIZING.

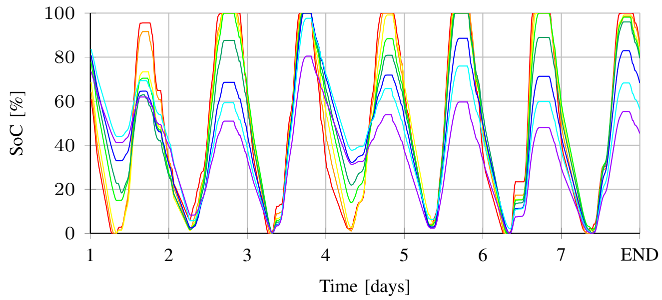
Equipment	**Size & configuration**
CHP unit	250 kW_{th} / 111 kW_{el}
CHP buffer	5 MWh (ATES)
Battery	6 kWh / house
PV panels	16 m^2 / house (19% eff.)

IV. RESULTS

Using the technologies as sized in Section III (see Table II), one year of the Markluiden soft-islanded microgrid is simulated using DEMKit [11], to evaluate its potential for two specific cases. The first case is the **NC** case, in which no control and optimization is applied, nor batteries are used.



(a) Electricity usage



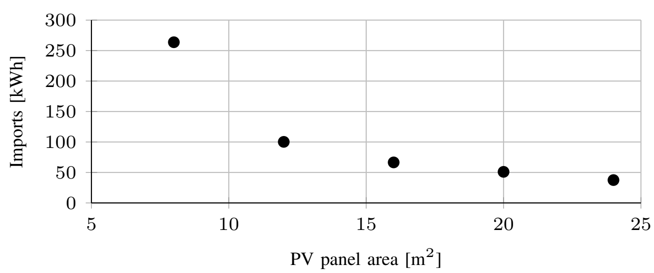
(b) SoC batteries.

Fig. 4. Electricity usage and battery SoC in week A for varied battery sizes

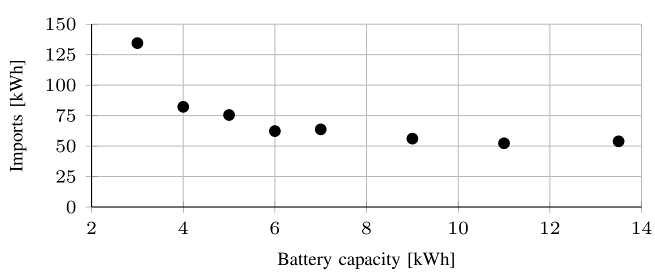
For the second case (**PS** case) optimization of storage and CHP operation is considered, meaning that we use Profile Steering [12] with the objective to minimize the quadratic deviation from the total power balance (0 W). Herein, Profile Steering uses a model predictive control method to optimize the energy profile for the upcoming two days using a rolling horizon approach. Furthermore, to resolve prediction errors, a double-sided auction [13] is used for operational control (see [11, Chapter 5] for more details). The two different cases are then compared with the present situation in Markluiden, the **R** (reference) case. For islanding the energy system, all the energy consumed within the system must be locally produced. This aspect is quantified with the DoA (see Section I).

In the R case, almost the entire electricity load comes from the grid. Only a small percentage of the total electricity demand of the 16 houses comes from the PV panels installed on the rooftop of one house. Consequently, the energy system is far from (soft-)islanded, with a resulting DoA of only 3.7%.

In the NC case, the yearly average electricity consumption per house is 3.7 MWh while the average electricity production per house is 16 MWh (see Table III). The average heat demand per house is 19.6 $\mathrm{MWh_{th}}$, which is completely satisfied by the heat produced by the CHP. The majority of the electricity (12.2 MWh per house) is generated by the CHP as a by-product of the heat generation. However, only 2.0 MWh of this production is used locally. The PV panels generate 3.8 MWh per house over the year but only 830 kWh is consumed locally. The excess electricity produced by the CHP and PV panels is 13.1 MWh per house for the entire year and is exported to the grid. On the other hand, 840 kWh is still imported. This yields a DoA of 77.3%, i.e. just over three quarters of the electricity load of the neighbourhood does not burden the grid. Although, this is a remarkable improvement compared to the R case, it is still far from soft-islanding the neighbourhood.



(a) PV panel area



(b) Battery capacity

Fig. 5. Necessary electricity imports for the considered battery capacities and PV panel areas during week A.

TABLE III
STATISTICS OF THE ANNUAL HOUSEHOLD ELECTRICITY USAGE.

Case	Import [kWh]	Export [kWh]	Production [MWh]	Consumption [MWh]	DoA [%]
R	4489.4	0.0	unknown	4.5	3.7
NC	839.27	13146.2	16.0	3.7	77.3
PS	401.5	12612.1	16.7	4.5	91.1

	Share in electricity supply [%]			
	Grid	**PV**	**CHP**	**BAT**
R	96.3	3.7	0.0	0.0
NC	22.8	22.4	54.9	0.0
PS	8.9	30.9	51.9	8.3

In the PS case, when energy storage is added, and double-sided auction control is applied, the results, compared to the NC case, are somewhat different. The yearly average electricity consumption is 4.5 MWh per house, while the production per house is 16.7 MWh. The increase in both production and consumption per house is mainly attributed to the battery, as discharging the battery is counted as production and charging the battery is counted as consumption. Still, the majority of the electricity (12.2 MWh per house) is generated by the CHP as a by-product of the heat generation. However, only 2.3 MWh of this is used locally. The PV panels generate 3.8 MWh per house per year of which 1.4 MWh is used locally. Furthermore, the average yearly electricity import has decreased, by over 50%, to 402 kWh per house. The average yearly export per house is decreased to 12.6 MWh. This yields a DoA of 91.1%, which is clearly an improvement to the NC case. Moreover, the battery usage is very limited, meaning that only 400 kWh (or 8.3%) of the total electricity demand is provided by the battery.

On the one hand, the neighbourhood performs much better in the PS case when compared to the NC case. More of the electricity generated by the PV panels is used locally, and less electricity is imported from the grid. On the other hand, for both the NC and PS case, the largest part of the consumed electricity is provided by the CHP unit. This is due to the high thermal demand. To illustrate this, in Figure 6 the electricity production for the neighbourhood during the simulated year is shown, note the high electricity production during winter.

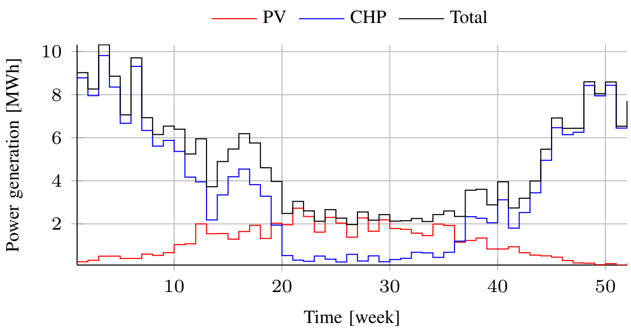


Fig. 6. Weekly electrical energy production of the CHP and all PV panels combined, resulting from sizing choices.

Hence, an improvement for this neighbourhood would be a reduction in its thermal demand through better insulation. Alternatively, one can conclude that the heat/electricity ratio of the CHP is far from optimal for this neighbourhood as discussed in [10].

V. Conclusions

In this work the practical applicability of soft-islanding is explored for an existing neighbourhood in Markluiden, the Netherlands, consisting of 16 houses. Based on the current physical characteristics of the 16 houses in the neighbourhood, the required size of a CHP, PV panels and a battery is determined.

If the soft-islanding approach is applied together with storage and optimal control, a DoA of 91.1% can be achieved. In this case, the electricity imported from the grid amounts to 402 kWh/year. However, the amount of electricity exported to the grid is quite high, at 12.6 MWh/year, meaning that the neighbourhood has quite a serious overproduction of energy. This is a very different operation of the system compared to the present situation in Markluiden (*R* case), where almost the entire electricity load is imported from the grid, with a resulting DoA of 3.7%. The large exports of electricity are clearly a consequence of the large heat demand, which results in a CHP producing too much electricity while fulfilling the heat demand. This implies also that the part of the year where the electricity production is dominated by the PV panels is only 16 weeks.

The substantial reduction of electricity imports from the grid between the R case (4.5 MWh/year) and PS case (0.4 MWh/year), shows that the soft-islanding approach also leads to a largely sustainable electricity supply when using bio-fuel for the CHP. However, aiming for a low electricity import and resulting low DoA could in this case have negative consequences. Because, in both the NC and PS case there is a significant electricity export due to the overproduction of electricity by the CHP, as a result of the high heat demand. Which could lead to an increased strain on the electricity grid compared to the R case.

Based on this, we conclude that first other steps are needed before installing a CHP, PV panels and batteries. It would be prudent to use the steps of *Trias Energetica* [18] and start by applying it's first rule: "Limit energy usage by reducing losses". Hence the houses should be properly insulated before any renewable energy sources are added or soft-islanding solutions are applied.

For future research PVT panels could be added to the neighbourhood model and equipment sizing. The heat produced by these panels could meet (part of) the heat demand, or could easily be stored in the ATES. This potentially results in a smaller sized CHP that is still sufficient to meet the remaining heat demand, in turn leading to less unwanted electricity exports.

Acknowledgements

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