CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Economics and Management

Diploma Thesis Title:

ENERGY SELF SUFFICIENCY ON CAMPUS

This Diploma Thesis has been written and defended at the **Cranfield University** in **United Kingdom** under the Double Degree Agreement between the Czech University of Life Sciences Prague, and the **Cranfield University**. In accordance with the Double Degree Agreement, this Diploma Thesis is fully recognized as part of the MSc programme study at the Czech University of Life Sciences Prague.

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CRANFIELD UNIVERSITY

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SCHOOL OF ENERGY, ENVIRONMENT AND AGRIFOOD
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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science

ABSTRACT

It is the aim of Cranfield University to improve the self sufficiency of the campus energy supply. One of the ways to do so is to introduce renewable energy. These are, however, affected by intermittency in energy supplies and thus pose challenges to the grid stability. Energy storage systems are widely recognised as one of the main ways to make renewables more reliable and also allow for peak shaving. Moreover, decreasing costs of such systems make it more attractive for those other than grid operators, such as Cranfield University. The aim of this thesis is to estimate the optimal parameters of such a solution (power and capacity), through an analysis of campus electricity consumption and afterwards to evaluate the financial feasibility for each system via net present value evaluation techniques and sensitivity analysis with different variables to determine under which conditions they are feasible. Capacity was calculated to 5 412.85kWh and power to 902.12kW. The approach showed that none of the five selected technologies were not economically feasible at given set of conditions. Conducted sensitivity analysis suggests that significant decrease of initial investment, longer payback period or increase in price of electricity make chosen technologies viable. The paper concluded that capacity and power parameters might be further used by the Facility office of Cranfield university on the field of electricity self sufficiency. It also concluded that the facility office might use its own confidential data to reach more accurate outcome.

Keywords:

Micro grid, Electricity storage, Electricity storage system, Battery, Flywheel, Fixed base index, Chain index, Net Present Value, Sensitivity analysis

ACKNOWLEDGEMENTS

The author is grateful for all the support and guidance to the thesis supervisor Dr. Nazmiye Ozkan. Further thanks are due to Gareth Ellis, Angus Murchie from the Facility office of Cranfield University, for their support and interest in this work.

To all the academic and administrative staff of the Cranfield University who helped me and made the experience possible.

Lastly, to all fellow students who inspired me in many ways and made Cranfield experience extraordinary and unforgettable.

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BEIS	Department for Business, Energy & Industrial Strategy
CCA	Climate Change Act 2008
CCC	Committee on Climate Change
CHP	Combined Heat and Power unit
CMP	Carbon Management Plan
CU	Cranfield University
DECC	Department for Energy and Climate Change
EC	European Commission
ESS	Electricity Storage Systems
EU	European Union
GBP or (£)	British pound sterling
HEFCE	Higher Education Funding Council of England
kW	Kilowatt
kWh	Kilowatt hour
MW	Megawatt
MWh	Megawatt hour
NPV	Net Present Value
PCA	The Paris Climate Agreement
UK	The United Kingdom of Great Britain and Northern Ireland
WEC	World Energy Council

1 INTRODUCTION

One of the major areas being discussed concerning climate change is with no doubt the way we use sources of energy, how they are delivered and generated and how they eventually affect our environment. Today, we see the use of coal as a traditional, yet no longer advantageous solution for the future energy supplies. The evidence of fossil fuel energy leaving its polluting footprints on our planet is clear. Growing public concern about the damages this traditional way of energy use can cause have lead the mankind to an urge to start finding new, non-polluting and preferably renewable sources of energy. The need of different approaches has brought new points of view on the pollution of the environment and thus led to various legal changes on the worldwide, as well as domestic, political scene.[1]

As affected by many newly created laws, which will be discussed further in this thesis, Cranfield University (further on referred to as CU) is obliged by a law to follow and implement UK energy policy targets. The university needs to find ways to reduce carbon emission production and thus avoid threat of paying significant penalties for not meeting the set requirements. As such, CU seeks for new ways to deal with energy use, using the maximum of renewable and clean sources of energy.

Renewable sources of energy increase the potential for creating self-sufficient micro grids within the grid. One possible solution to help to balance the grid, to protect vital infrastructure and to increase the energy security is the use of Electricity Storage Systems (ESS). Moreover, the efficient use of ESS may ideally lead to the reduction of electricity bills. It is the aim of this thesis to find out what size of ESS is optimally needed for CU, to compare the economic feasibility of chosen ESS under the specific conditions of CU and to determine under which conditions they are feasible.

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[1] Some of the most important documents will be further described in the Literature review

Firstly, the literature review section provides an overview of UK government moves in the area of environment and energy that has led to the increased attractiveness of renewable electricity in the energy mix and consequently to rising desirability of ESS. This section also provides fundamental technical information about chosen ESS. Secondly, the methods section specifies approaches used to achieve these results. The results section contains a description of the procedures used to reach outcomes and results themselves. The discussion section compares the outcomes of this thesis with the other research papers and it is followed by conclusions and recommendations section.

2 Literature review

The aim of this section is to offer a theoretical background to the topic of self-sufficiency and rising attractiveness of energy storage systems as a prospective solution. Furthermore, it is intended to provide an overall understanding of the UK government steps in time in the environmental and energy field, this section also ought to provide elementary technical characteristics of the proposed ESS and its energy conversion ratio.

2.1 Environment and energy policy drivers

The 2020 climate and energy package, agreed by leaders of European Union (EU) in 2007, came into force 2009 (European Commission, 2016). The UK agreed to the package with the requirements of a 16% decrease in greenhouse gas emissions from 2005 levels and a 15% share of renewables in energy mix production, both to be fulfilled by the year 2020 (European Commission, 2010).

In the light of this commitment, Parliament of the United Kingdom approved Climate Change Act 2008 (CCA) and its amendments. Furthermore, the bill also provides the basis for the creation of Committee on Climate Change (CCC) as an advisory body of Sectary of State, whose duty is to ensure that the UK meet the announced commitments. Compared to baseline in 1990, the UK pledges to reduce its level of targeted greenhouse gases emissions (carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride and any other greenhouse has designed as a targeted by the Secretary of State) by at least 80percent by the year 2050. Moreover, the bill claims the subordination to the European or international law or policy (Parliament of the United Kingdom, 2008).

Further essential aims are stated in Article 2 of The Paris Climate Agreement (PCA), an international agreement within the United Nations Framework Convention on Climate Change; it specifically states to:

- Keep the rise of the "*global average temperature well below 2°C above the pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change and pursuing efforts to limit the*

> *temperature increase to 1.5°C above pre/industrial levels, recognizing that this would significantly reduce the risk and impacts of climate change* " (UNFCCC. Conference of the Parties, 2015).

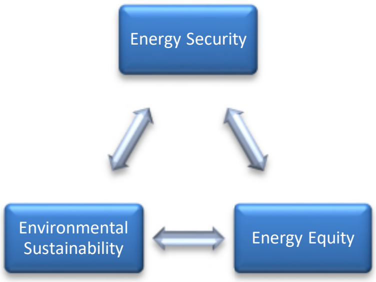
The PCA also sets a five-year cycle of pledges and reviews of taken action and goals on the national and international level. The UK ratified the agreement on the 18th of November 2016 (BEIS, 2016). According to the recommendation of CCC, the long-term perspectives of Paris climate agreement are in alignment with CCA and the intended 80percent greenhouse gas reduction by 2050. In a mid-term perspective, the UK government ought to aim to support the research, development, and demonstration of technical, environmental and social solutions to successfully fulfil long-term schemes. Near or short-term plans of the government ought to be to "*publish a robust plan of measures to meet the legislated UK carbon budgets, and deliver policies in line with the plan*" (Bell *et al.*, 2016).

Environmental drivers such as Paris Climate Agreement, together with the EU's 2020 climate and energy package and CCA, have motivated the UK's initiation of the national targets for emission reduction by financial incentives (HM Treasury, 2016). One of the ways to achieve the targeted decrease of emission is to reduce their production in the energy field, by the support of either low carbon generation, or increasing effectiveness. Therefore, energy policy would most certainly be influenced by emission reduction target

There are two major documents which define the UK's energy policy; the Energy white paper (DECC, 2012) and the UK Low carbon transition plan (HM Government, 2009). These documents aim to increase the renewable electricity output by around 30 percent by 2020. An increase of renewables, however, inevitably influences the balance of energy trilemma.

World Energy Council (WEC) defines energy trilemma based on "*how well countries balance the three often conflicting goals of energy sustainability – energy security, energy equity, and environmental sustainability*" (WEC, 2013). In other words, the energy trilemma represents a secure energy supply (energy security) in a sense of operational reliability of energy infrastructure and an ability to meet existing or future energy demand. Thus, energy equity signifies the accessibility and affordability of energy supplies for the inhabitants. Furthermore, environmental sustainability may be defined as: *The achievement of supply and demand-side energy efficiencies and the development of energy supply from renewable and other low-carbon sources* (WEC, 2013).

Figure 1 - Energy trilemma



Source: (WEC, 2013)

In response to the above-described challenges, and also to the demand of former Secretary of State for Innovation, Universities and Skills (current Secretary of State for Business, Energy and Industrial Strategy), the Higher Education Funding Council of England (HEFCE) has developed two documents. Firstly, the carbon reduction targets and strategy for higher education institutions in England (HEFCE, 2010b) sets out a revised strategy for this sector, and secondly, the Carbon management strategies and plans: A guide to good practice "*provides good practice guidance for institutions on producing individual carbon reduction strategies, targets and associated Carbon Management Plans*" (HEFCE, 2010a).

It is clear that Cranfield University (CU) certainly belongs among the higher education institutions in England (HEFCE, 2017). Therefore, CU had to respond to those two external documents by developing its own, approved by executives, Carbon Management Plan (CMP) and also in response to Carbon Reduction Commitment Energy Efficiency Scheme, "*which carries financial benefits or penalties for good or poor performance respectively*" (CU, 2011a). The Carbon Reduction Commitment Energy Efficiency Scheme was later replaced by the Climate Change Levy, which is supposed to also "*reduce administrative costs and improve incentives to invest in energy efficiency*" (HM Treasury, 2016)

In the academic year of 2015/2016 CU's Annual Environment Report announced a plan of installation of renewable energy schemes in near future (Board for Energy and Environment, 2016). Based on the information provided by the management of Facility office of CU, it has been discovered that by April 2018, a new photovoltaic park ought to be installed within the campus.

CU contributes to the global, government and HEFCE carbon reduction plans by the development of its own energy policy. Moreover, it follows the Carbon Reduction Commitment Energy Efficiency Scheme, which carries financial benefits or penalties for either good or poor performance respectively. CU energy policy has been developed with a reference to the Cranfield University CMP (CU, 2011a). Among others, the document also states that it is necessary "*to encourage better use of energy and the need to reduce emissions to all staff and students*" (CU, 2011b). CU is planning to install a renewable source of electricity, which will contribute to the aforementioned aim[2], but will also influence local micro grid energy trilemma. A new renewable source of electricity ought to improve energy security by creating local micro grid more independent and improving environmental sustainability by introducing the renewable source of electricity.

2.2 Technical characteristics

The term micro grid may be understood differently and therefore cause misunderstanding. For the purpose of this thesis, the term micro grid will be interpreted according to the definition of U.S. Department of Energy: "*A micro grid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A micro grid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode*" (U.S. Department of Energy, 2011). Micro grids could be further differentiated into industrial, community, remote, military or campus micro grids (The Electric Power Research Institue, 2016). CU is apparently campus type of micro grid with the connection to the grid. However, CU is not permitted to send out (to the grid) electricity surpluses obtained from renewable or any other source of energy**Error! Bookmark not defined.**.

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[2] The above stated information was provided by Mr. Angus Murchie, energy advisor and by Mr. Gareth Ellis, Energy & Environment Manager, both from Facility office of CU.

2.2.1 Electricity Storage Systems

There are several possible technical solutions for campus micro grid. One of them is electricity storage system (ESS). Based on the data about electricity use within the campus, which were assessed and provided by Facility office of CU, the parameters (capacity and power) of potential solutions were identified. Setting those parameters helps to reduce range or possible solutions, as some of them are designed by scale parameters or topography requirements for other than campus micro grid. The approach of calculating those parameters will be described in depth later in subsection 4.2. It is possible to say that capacity has been set to be 5412.85kWh and power 902.14kW.

The capacity of ESS is frequently discussed as a means capable of providing power over a specific time, kilowatt hours (kWh) or Megawatt hours (MWh). Power capability is another equally important metric, which expresses the power which ESS can provide. It is measured in kW or MW. Another important measurement is percent efficiency conversion, which indicates the amount of electricity brought back during discharge from fully charged ESS (Grothoff, 2015). Values for each considered technology are stated in Table 1 on page 8.

Energy might be stored in ESS during the time when the energy output supply is greater than the demand and therefore it is returned to the grid whenever required. As such, energy is not wasted. This situation occurs in the case of both renewable or classic (fossil-use or nuclear power), rather linearly producing (base load) types of sources (Boyle, 2012). Using electricity from the grid to charge ESS (store electricity) when the price of electricity is low, and to discharge when the price is high, is called peak shaving.

2.2.1.1 Battery storage system

Considered batteries are commercially produced and operated rechargeable batteries, which store electric energy by applying different electrochemical processes. Industrially produced battery storage systems are equipped with monitor and control systems which prevent overheating or deep discharge which could shorten intended lifecycle (Boyle, 2012). Considered technologies are

Lithium-Ion (Li-Ion), Lead-Acid, Sodium Sulphur (Na/S) and Vanadium Redox flow battery.

2.2.1.2 Flywheel energy storage system

The flywheel energy storage approach has been known for a long time. However, due to the recent technology and material development, it seems to be more promising (Mahlia *et al.*, 2014). “*Flywheels store energy in the form of the angular momentum of a spinning mass, called a rotor. The work done to spin the mass is stored in the form of kinetic energy*”(Huff *et al.*, 2013).

Table 1 – Technology efficiency conversion

Battery technology	Efficiency (%)	Source
Lithium-Ion (Li-Ion)	88	Tesla (2017)
Lead-Acid	90	Huff *et al.* (2013)
Sodium Sulphur (Na/S)	75	Huff *et al.* (2013)
Vanadium Redox	80	Gildemeister (2017)
Flywheel	90	Mahlia *et al.* (2014)

3 Methods

This section will provide information about used research methods so that work can be reproduced.

3.1 Data analysis

Data analysis has been done by chain and fixed base indexes to identify trends in time series. Arithmetic mean and standard deviation were used for representation and consideration of variation during the capacity and power calculation.

3.2 Financial evaluation

A number of recent articles have applied the economic evaluation in relation to micro grid or energy storage (Yan *et al.*, 2014; Dufo-López and Bernal-Agustín, 2015; Masebinu *et al.*, 2017).

Originally, it was intended to use the net present value formula with values based on the data provided by already existing UK based ESS operators. However, neither they nor the commercial producers were willing or permitted to share the required data. Furthermore, the Facility office of CU could not provide needed data about planned photovoltaic installation. Therefore, it was decided to use the data from the already existing literature (Zakeri and Syri, 2015). The needed data were founded in appendix A. The data were used for initial investment calculation as well as for calculation of inflows and outflows.

Net Present Value (NPV) is the financial quantity that expresses the total present value of all cash flows associated with the investment project. Net present value is used as a criterion for evaluating the return on investment projects. It can be either positive or negative, where negative outcome ought to be refused as an unattractive project from the financial point of view. Project attractiveness increases with increasing NPV.

Equation 1 - Net Present Value

$$NPV = \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} - I$$

Source: (Larrabee and Voss, 2012)

The equation represents formula which was used for financial evaluation of projects. The “I” represents the initial investment. The sum of financial inflows and outflows is represented by “CF_t”. The value of money in time (interest rate) is characterised by “r” and “t” stands for time, number of periods (Gitman., 2005).

3.3 Sensitivity analysis

Sensitivity analysis is a calculation method that examines the effect of changing the input variables on their outputs (results). The purpose of sensitivity analysis is to determine the sensitivity of the outputs to individual or combined inputs and to determine how these inputs affect the overall result. To perform a sensitivity analysis, it is necessary to have a model of calculation, so the sensitivity analysis is the last step of the computational operations (Cacuci, Ionescu-Bujor and Navon, 2003; Larrabee and Voss, 2012)

4 Results

Firstly data analysis will be conducted to identify trends in annual, seasonal and daily consumption patterns. Secondly, based on previously finished analysis, calculation of capacity and power of energy storage system will be done. Lastly, net present value evaluation together with sensitivity analysis will be done base on acquired data.

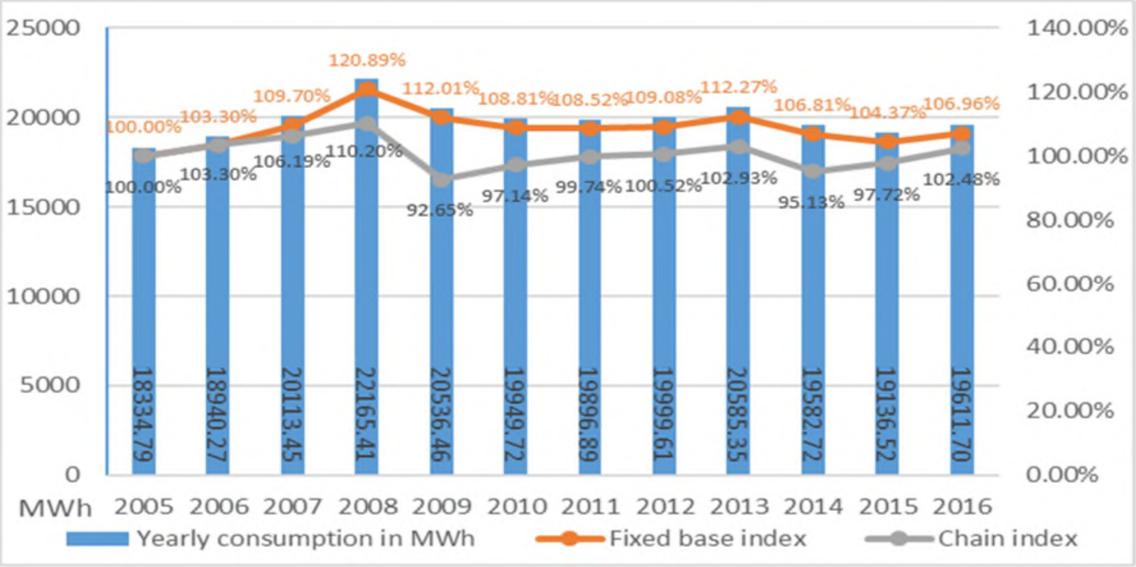
4.1 Data analysis

Data analysis based on historical data was carried out to determine trends in on campus electricity consumption so to that the optimal parameters (capacity and power) of ESS are relevant to current campus needs. Data were provided by Facility office of CU. Chain and fixed base indexes help to indicate changes in observed data from different perspectives. An overview of development in time is provided by time series.

4.1.1 Annual electricity consumption trends

Firstly, it was decided to analyse trends in campus electricity consumption over the years to identify potential long-term patterns.

Figure 2 - Trend analysis of annual electricity consumption on campus



Source: Facility office of CU, Author's work

The chain index of Figure 2 - Trend analysis of annual electricity consumption on campus shows that electricity consumption was relatively constant. Apart from the peak variation of 10% in 2007-09, the year-to-year variation was generally around 5%. Fixed base index compares consumption over the years with a base year. The year 2005 was chosen as a base year as it was the earliest available. This measure of consumption also appeared to be relatively constant, without significant increase or decrease except the year 2008, when the increase was 21% compare to the base year. It should be pointed out that yearly consumption may also be influenced by outside, uncontrolled factors such as extreme weather condition. It is possible to say that both indexes prove stable yearly electricity consumption, oscillating around the 20 000 MWh mark yearly, despite the development of campus facilities. It is also possible to say that there is not expected to be a major increase in electricity consumption in the near future, since CU is committed maintain or improve its energy efficiency/consumption as stated in (Board for Energy and Environment, 2016)

4.1.2 Seasonal consumption trends

The monthly analysis was done in order to identify seasonal patterns in electrical consumption within the campus. The time period starting in April 2016 and ending in March next year was chosen for two reasons. First, the fact that heating season in UK is divided into two periods. Summer runs from the 1st of April to the 30th of September and the winter season from 1st October to 31st March, therefore seasonality should have been apparent. Second, it tied with pricing changes from university electricity provider[3].

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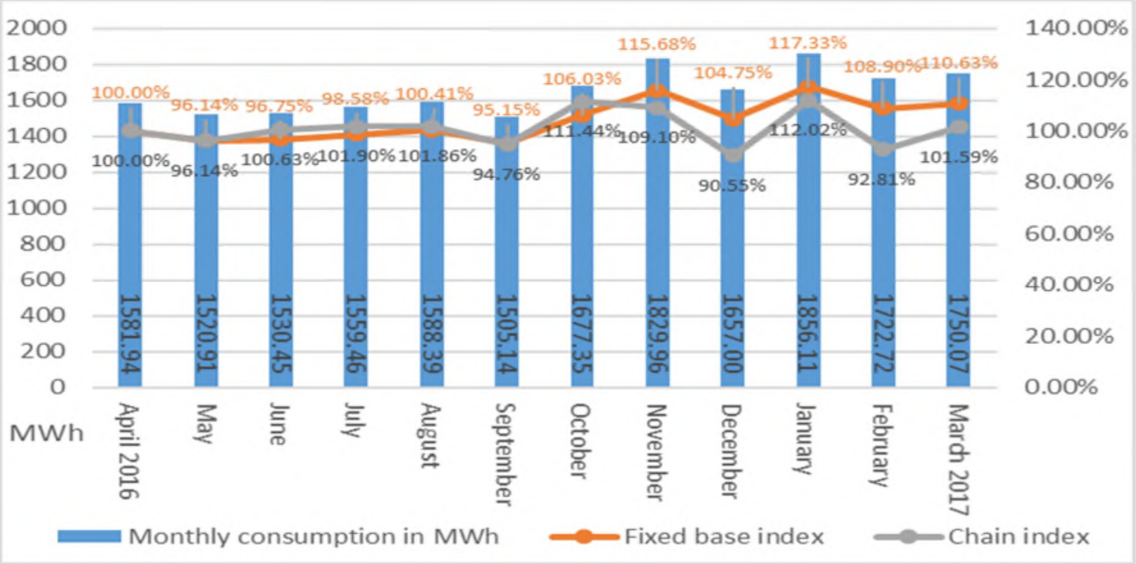
[3] The above stated information was provided by Mr. Gareth Ellis, Energy & Environment Manager and by Mr. Angus Murchie, energy advisor, both from Facility office of CU.

Figure 3- Trend analysis of monthly electricity consumption on campus



Source: Facility office of CU, Author's work

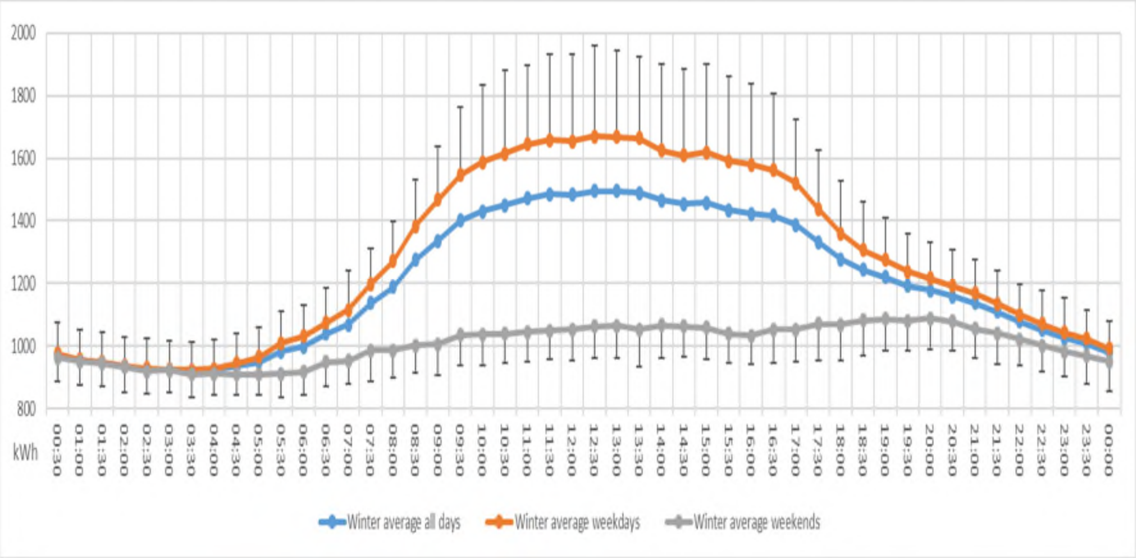
The chain index of Figure 3 indicates several noticeable decreases and increases in consumption throughout the chosen time period. The decreases in May and September could have been caused by fewer students living in and using campus facilities as they major study duties finished and they left. The December decrease could have been caused by Christmas break when the majority of students and academic staff left and the campus is not fully operational for almost two weeks. The February decrease could have been caused either by fewer days in a calendar month in comparison with January or by different weather condition. Significant increases followed previous decreases but general trends support the idea of seasonality. The fixed base index also supports the idea of seasonality as data shows the significant increase in comparison with the base month in winter season months. Reasons for decreases in this index are likely to be same as in previous one. Overall winter electricity demand is approximately 1200 MWh (13%) higher than summer demand.

4.1.3 Daily electricity consumption trends

Previously conducted analysis proves the influence of seasonality on electricity consumption. Therefore, the winter period (from 1st October to 31st March) was chosen to be closer analysed due to its higher demand. This higher demand might be caused by additional electric heating, lack of daylight in comparison with summer time (therefore more lights ought to be turned on) and higher consumption of hot beverages probably produced by kettles. Half hourly, average values together with their standard deviation sufficiently represent the variation of consumption.

Daily electricity consumption analysis ought to show differences in electricity demand during the day and night and also illustrate the importance of academic and research related activity in electricity demand.

Figure 4 - Winter, half hourly analysis of electricity consumption on campus



Source: Facility office of CU, Author's work

Figure 4 shows that average electricity consumption within the campus varies significantly during the daytime and between weekdays and weekends. Night consumption does not vary significantly. Higher weekday daytime consumption is probably caused by the activity of academic staff and students, meanwhile weekend daytime consumption appears to be noticeably both lower and stable reflecting not pursuing any electrically demanding activity such as experiments or other research activities etc. and be kept stable due to the accommodation facilities. For a more detailed look, please see appendix A.

4.1.4 Cranfield University electricity supply

The CU micro grid is currently supplied from two sources. Firstly, CU uses combined heat and power unit (CHP) which is capable of producing up to 1.5MWh of electricity (750kWh half hourly). However, it is not used at maximum[4]. CHP does not cover CU electricity needs. The rest of supplies is covered by electricity from the grid. The gap between them (CHP production and CU el. demand with standard deviation) was identified as the area to determine optimal parameters of ESS.

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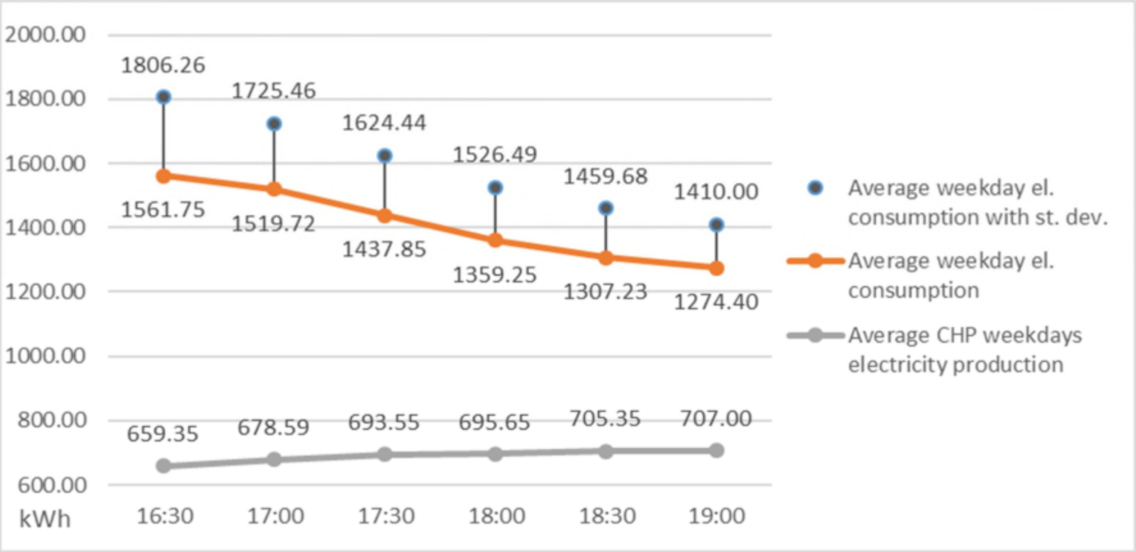
[4] The above stated information was provided by Mr. Gareth Ellis, Energy & Environment Manager and by Mr. Angus Murchie, energy advisor, both from Facility office of CU.
This information was also proven by data analysis. For more details, please look at appendix B.

4.2 Calculation of capacity and power of ESS

Based on the data analysis and consultation with Facility office, and information about the future pricing rates for electricity, the 4 - 7pm time slot of average winter weekdays (consumption and production) was chosen for capacity and power calculations. ESS is aimed to be charged and discharged on average once a day to allow for peak shaving.

Figure 5 - Energy storage system parameters calculation



Source: Facility office of CU, Author's work

Figure 5 displays the values used for capacity calculation. It adds differences between average CHP weekday production and average weekday electricity consumption with standard deviation. The sum is 5 412.85kWh. Power was derived by dividing the capacity by the number of observed periods (6; 16:30-19:00), hence 902.14kW. Those values are optimal and they might not be achieved by chosen technologies in reality, but for the purposes of this thesis, it is assumed they are capable of doing so.

However, due to the losses occurring during charging and discharging, parameters of ESS need to be adjusted so that desired outcome (electricity supply) is achieved. Adjustment calculation has been done in Table 2 using values about efficiency from Table 1, on page 8.

Table 2 – Calculation of extended technological parameters of ESS

Technology of ESS	Lithium-ion	Lead-Acid	Sodium Sulphur	Vanadium Redox	Flywheel
Capacity (kWh)	5,412.85	5,412.85	5,412.85	5,412.85	5,412.85
Power (kW)	902.14	902.14	902.14	902.14	902.14
Efficiency (%)	0.88	0.89	0.75	0.88	0.90
Extended capacity (kWh)	6,150.97	6,081.85	7,217.13	6,150.97	6,014.28
Extended power (kW)	1,025.16	1,013.64	1,202.85	1,025.16	1,002.38

Source: Author's work

Table 2 shows how extended capacity and extended power proportionally increased in accordance with values from Table 1 so that desired (optimal) capacity and power ought to be achieved.

4.3 Net Present Value

The previous part was devoted to estimation of optimal parameters of ESS. Those parameters will be used in this part too. ESS might be also analysed from the financial point of view as an investment opportunity under specific CU conditions. Net Present Value (NPV) evaluation technique was used for conduction of financial feasibility comparison of intended ESS. CU is financing energy projects by Salix Finance Founding[5]. Salix Finance is a government fund which provides interest-free loans to the public sector (e.g. to higher education institutions in England) to allow energy efficiency projects, carbon emission reduction or decrease in energy bills (Salix Finance, 2017a). ESS installation within the campus ought to contribute to all those above-mentioned aims.

4.3.1 Initial data

As mentioned in the methodology, commercial producers of ESS or UK based ESS operators were not willing or permitted to provide data needed for conduction of the analysis, and neither could Facility office of CU. Therefore, those data were extracted and adjusted to the intended parameters of ESS. The

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[5] The above stated information was provided by Mr. Gareth Ellis, Energy & Environment Manager from Facility office of CU.

source of those data is a journal article of Zakeri and Syri (2015). However, the values contained in this journal are stated in euros, therefore they were converted to GBP according to exchange rate valid on the 1st of January 2015, where one pound was worth 1.2878 euros (Bank of England, 2017). Also, as the values are from year 2015, they need to be increased by inflation, so that they reflect prices in 2017. GDP deflator was used with value increase of 1.99% between financial years 2015-16 and 2016-17 (HM Treasury, 2017).

4.3.2 Assumptions

This subsection contains list of assumption applied for the NPV calculation. The assumptions are:

- The effectiveness of the intended ESS over time is considered to be stable
- The prices of electricity for charging and discharging are assumed to be persistent
- The number of charging and discharging cycles per year is constant
- There is no change in annual maintenance costs
- The costs associated with the ecological disposal are not included as the life cycle of all considered ESS should be longer than payback period.

4.3.3 Length of evaluation and discount rate

Certain evaluation criteria were set out in accordance with Salix Finance's conditions, such as the interest-free 5 year payback period (Salix Finance, 2017b) as can be seen in Table 3. Therefore, value of money over the time actually does not play a role. This is one of the specific CU conditions.

Table 3 – Salix Finance conditions

Discount rate (%)	0.00
Number of payback periods (years)	5.00

Source: (Salix Finance, 2017b)

4.3.4 Initial investment

Initial investment expresses the amount of money needed for acquiring chosen technologies.

Table 4 provides information about unit and total costs of technology parts needed for acquiring energy storage systems.

A power conversion system, as a technological part, ought to cover costs related to the technology of voltage, current and other power features of the ESS. A storage section as another technological part, is related to the cost associated with ESS itself. Average unit values were found in aforementioned literature and modified as is described in 4.3.1.

Initial investment for each ESS technology was derived from the extended capacity and extended power specified for each ESS technology in Table 2, page 17. Those values were multiplied by the unit price (GBP/kW for extended power or GBP/kWh for extended capacity) of each technological part stated in Table 4, below. Therefore, total values for each part could be computed and displayed (also in Table 4) below the unit price. Initial investment is sum of total costs of power conversion system and storage section.

Table 4 - Initial investment calculation

Technology of ESS	Lithium-ion	Lead-Acid	Sodium Sulphur	Vanadium Redox	Flywheel
Power Conversion System (£/kW)	366.68	299.36	289.86	388.07	227.30
Storage Section (£/kWh)	629.62	489.44	236.01	369.85	2229.40
Power Conversion System (£)	375,908.38	303,448.84	348,661.11	397,829.60	227,836.38
Storage Section (£)	3,872,751.40	2,976,690.16	1,703,296.15	2,274,936.99	13,408,217.71
Initial investment (£)	**4,248,659.78**	**3,280,139.00**	**2,051,957.26**	**2,672,766.59**	**13,636,054.09**

Source: Author's work

Table 4 provides detailed information about initial investment about each technology. Values from last row, initial investment, show the value which will be used in NPV calculation.

4.3.5 Inflows and Outflows

Inflows, in this case are understood as potential savings from electricity bills which CU could achieve by operating ESS. Inflows take advantage of price differences of electricity throughout the day. Outflows are costs related to the running of the ESS. They include yearly maintenance of the system and value of electricity used for charging ESS. Both, inflows and outflows are considered to be achieved at the end of each period.

The price of electricity influences inflows and outflows calculation. The Facility office of CU provided data about electricity rates which will be applied at the university from October 1st, 2017. There are three rates with different pricing. This electricity pricing is another specific condition of CU.

Table 5 – Variation in electricity prices by different daytime period

Rate	Rate 1 (Red)	Rate 2 (Amber)	Rate 3 (Green)
Time	4pm -7pm	7am - 4pm	7 pm - 7am
Price (£/kwh)	0.25321	0.10123	0.08321

Source: Facility office of CU

Table 5 indicates that rate one (red) is the most expensive, three times more expensive than the cheapest electricity rate, rate three (green), provided to CU. Those two were also chosen for further calculation.

What is not included in inflows calculation and probably ought to be, are Triad charges, which applies monthly across the year as a part of the Distribution Network use of Service charges. What those charges will actually be is worked out based on electricity use during the 3 half hourly Triads retrospectively identified in April every year by National Grid[6]. Unfortunately, Facility office could not reveal those (even historical) data as they are confidential. Those charges could be also understood as a saving as those charges contribute to the overall electricity bills paid by CU.

For the calculation conducted in Table 6 it is assumed that charging and discharging cycle is done in average once a day, therefore 365 times a year. Rate 1 was used for calculation of inflows (savings) as it matches with chosen time slot and price of electricity is highest, therefore biggest savings are possible. This value (0.25321£/kWh) was multiplied by the optimal capacity of ESS (5 412.85kwh) and 365. For outflows, Rate 3 (0.08321£/kWh) was used for

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[6] The above stated information was provided by Mr. Gareth Ellis, Energy & Environment Manager from Facility office of CU.

charging period. As such, it was multiplied by the value of the extended capacity of each ESS (see Table 2) and 365. Maintenance unit value was multiplied with extended power value for each particular ESS from Table 2. Thus, we can see the annual maintenance cost in the row below. Net Cash Flow stands for the sum of inflows minus outflows. In this case, the value of electricity for charging and maintenance representing outflows is subtracted from the value of electricity for discharging standing for inflows.

Table 6 - Cash flow calculation

Technology of ESS	Lithium-ion	Lead-Acid	Sodium Sulphur	Vanadium Redox	Flywheel
Electricity for discharging (kWh)	1,975,690.25	1,975,690.25	1,975,690.25	1,975,690.25	1,975,690.25
Value of electricity for discharging (£)	500,264.53	500,264.53	500,264.53	500,264.53	500,264.53
Electricity for charging (kWh)	2,245,102.56	2,219,876.69	2,634,253.67	2,245,102.56	2,195,211.39
Value of electricity for charging (£)	186,814.98	184,715.94	219,196.25	186,814.98	182,663.54
Maintenance (£/kW -yearly)	5.46	2.69	2.85	6.73	4.12
Maintenance (£)	5,602.09	2,729.43	3,429.45	6,901.13	4,128.05
Net Cash Flow	**307,847.45**	**312,819.16**	**277,638.83**	**306,548.42**	**313,472.94**

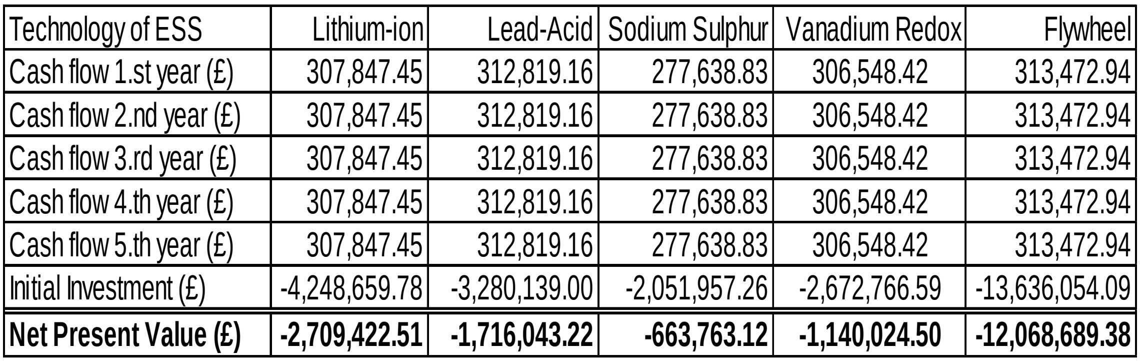
Source: Author's work

Table 6 provides comprehensive information about the calculated inflows and outflows of each ESS. Net cash flows are all positive numbers, therefore all ESS ought to be operationally profitable.

4.3.6 Calculation of NPV

Net present value calculation allows for a financial feasibility comparison of each ESS technology. As already mentioned, Salix Finance provides interest-free 5 years loans, so the value of money over the time is not actually taken into account. Each cash flow represents net cash flow for the given year, calculated in Table 6. Initial Investment is a negative number as it is subtracted from the sum of all cash flows. Values are taken from Table 4. Net present value is the sum of all the above.

Table 7 - Net present value calculation



Technology of ESS	Lithium-ion	Lead-Acid	Sodium Sulphur	Vanadium Redox	Flywheel
Cash flow 1.st year (£)	307,847.45	312,819.16	277,638.83	306,548.42	313,472.94
Cash flow 2.nd year (£)	307,847.45	312,819.16	277,638.83	306,548.42	313,472.94
Cash flow 3.rd year (£)	307,847.45	312,819.16	277,638.83	306,548.42	313,472.94
Cash flow 4.th year (£)	307,847.45	312,819.16	277,638.83	306,548.42	313,472.94
Cash flow 5.th year (£)	307,847.45	312,819.16	277,638.83	306,548.42	313,472.94
Initial Investment (£)	-4,248,659.78	-3,280,139.00	-2,051,957.26	-2,672,766.59	-13,636,054.09
Net Present Value (£)	**-2,709,422.51**	**-1,716,043.22**	**-663,763.12**	**-1,140,024.50**	**-12,068,689.38**

Source: Author's work

Table 7 provides detailed information about calculations of net present value of each considered ESS technology under specific CU conditions. It also shows that under those conditions, all of them ought to be refused as an investment as all of them are negative values. The least negative (minus) value seems to be sodium sulphur ESS technology with - 663 763.12 GBP value and the highest negative value flywheel ESS technology with – 12 068 689.38 GBP. For further details of the calculations, please see appendix C.

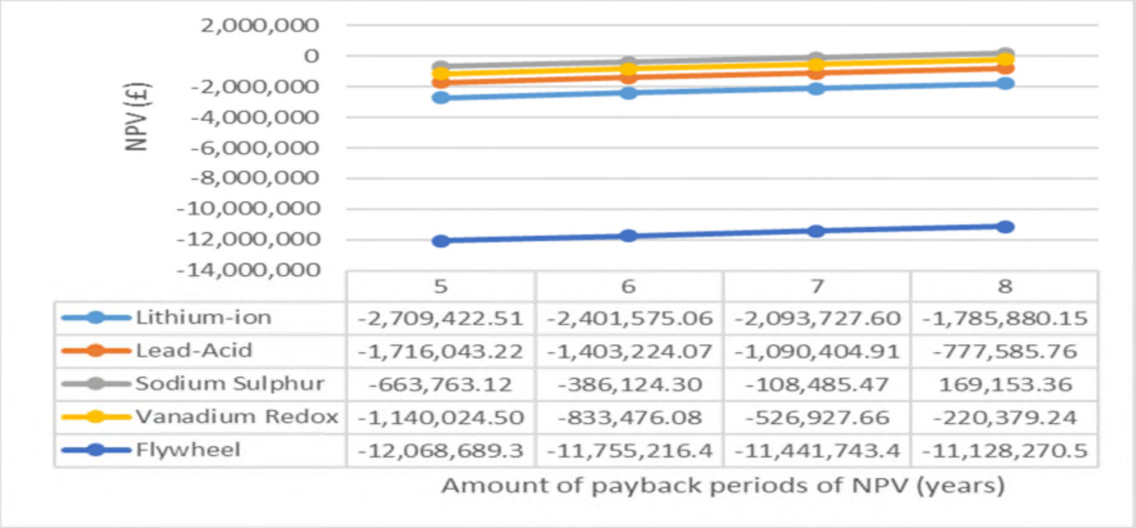
4.4 Sensitivity analysis

This section examines the change of values of NPV resulting from the change of input variables. Each change of variables represents a different scenario. Chosen variables are: length of evaluation; money needed for initial investment (storage section and power conversion section unit price); and price of electricity for charging and discharging. Other (not chosen) variables are efficiency, discount rate, number of charging and discharging cycles and maintenance unit cost. There are, in total, 9 variables.

4.4.1 Scenario 1

Scenario 1 shows NPV with different, longer payback periods. The payback period was extended up to 8 years to find out how it influences NPV results every added year.

Figure 6 - Scenario 1



	5	6	7	8
Lithium-ion	-2,709,422.51	-2,401,575.06	-2,093,727.60	-1,785,880.15
Lead-Acid	-1,716,043.22	-1,403,224.07	-1,090,404.91	-777,585.76
Sodium Sulphur	-663,763.12	-386,124.30	-108,485.47	169,153.36
Vanadium Redox	-1,140,024.50	-833,476.08	-526,927.66	-220,379.24
Flywheel	-12,068,689.3	-11,755,216.4	-11,441,743.4	-11,128,270.5

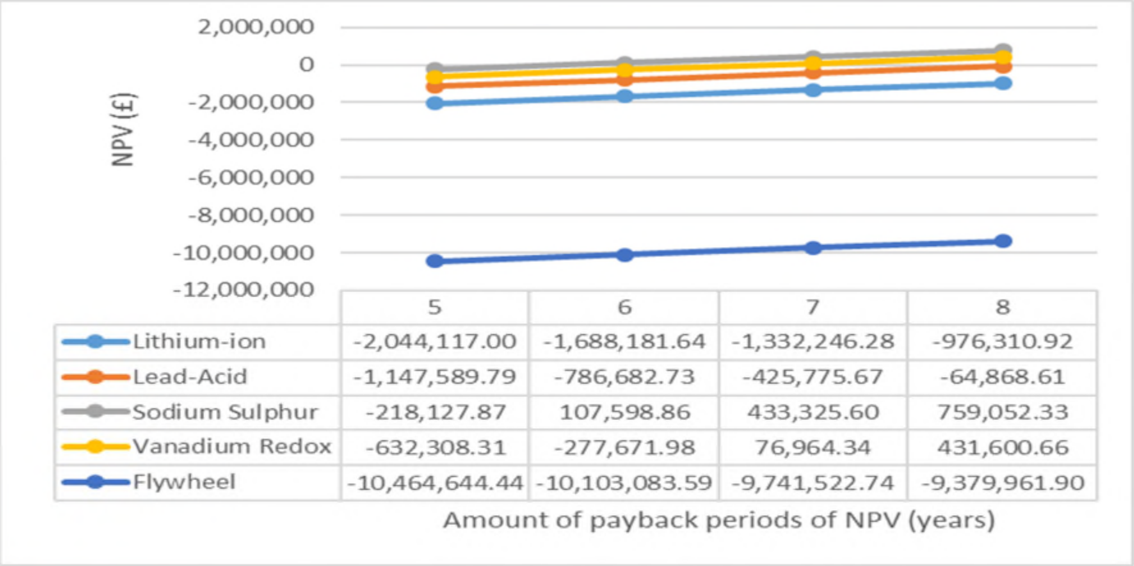
Source: Author's work

Figure 6 demonstrates how the length of payback period influences final NPV. Sodium Sulphur ESS would be, under given the condition (8 year payback period), accepted as an investment as its NPV is positive.

4.4.2 Scenario 2

Scenario 2 represents NPV with longer payback periods, a 10% lower initial investment to all ESS and a 10% higher price of electricity for discharging.

Figure 7 - Scenario 2



	5	6	7	8
Lithium-ion	-2,044,117.00	-1,688,181.64	-1,332,246.28	-976,310.92
Lead-Acid	-1,147,589.79	-786,682.73	-425,775.67	-64,868.61
Sodium Sulphur	-218,127.87	107,598.86	433,325.60	759,052.33
Vanadium Redox	-632,308.31	-277,671.98	76,964.34	431,600.66
Flywheel	-10,464,644.44	-10,103,083.59	-9,741,522.74	-9,379,961.90

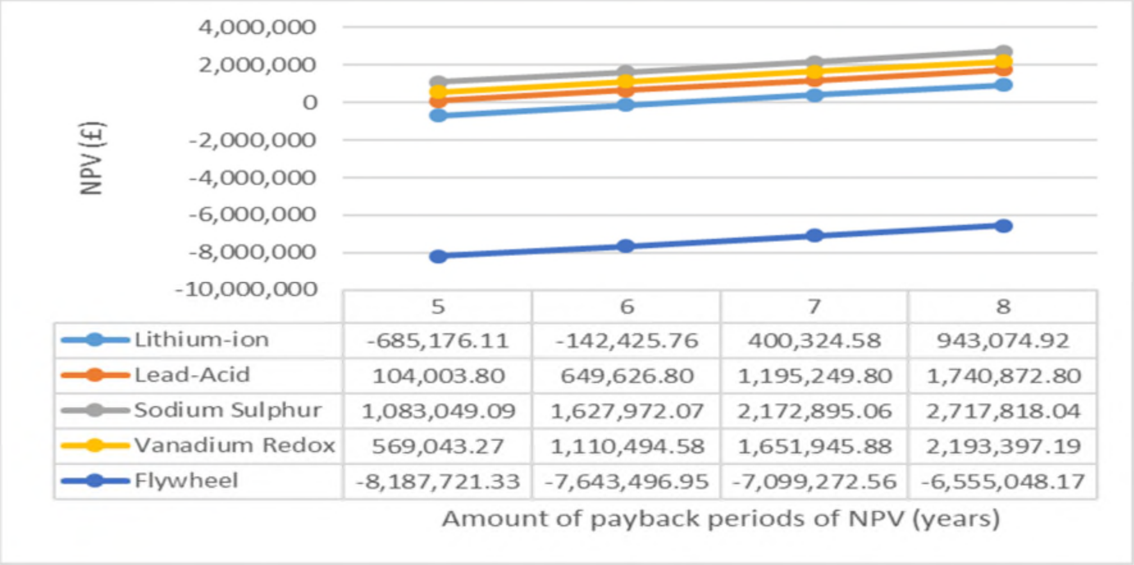
Source: Author's work

Figure 7 shows how is NPV influenced under these different sets of conditions, specified in 23Scenario 2. In this case, Sodium Sulphur became profitably acceptable at end of the 6th year and Vanadium Redox at end of the 7th year. Both can be recognized as an investment opportunity, however, the higher positive value makes Sodium Sulphur technology the preferred choice.

4.4.3 Scenario 3

Scenario 3 represents NPV with longer payback periods, a 20% lower initial investment to ESS, a 10% higher price of electricity for discharging and zero price of electricity for charging.

Figure 8 - Scenario 3



	5	6	7	8
Lithium-ion	-685,176.11	-142,425.76	400,324.58	943,074.92
Lead-Acid	104,003.80	649,626.80	1,195,249.80	1,740,872.80
Sodium Sulphur	1,083,049.09	1,627,972.07	2,172,895.06	2,717,818.04
Vanadium Redox	569,043.27	1,110,494.58	1,651,945.88	2,193,397.19
Flywheel	-8,187,721.33	-7,643,496.95	-7,099,272.56	-6,555,048.17

Source: Author’s work

Figure 8 indicate changes of NPV according to the conditions of Scenario 3. Sodium sulphur and Vanadium Redox ESS could be considered as a prospective investment after the 5th year of payback period. It is possible to say that flat reduction of initial investment by a fifth significantly increases final NPV, therefore it can be concluded that initial investment is an important variable.

4.4.4 Scenario 4

It was decided to determine what ought to be the prices of electricity for discharging (keeping all other variables the same) in order to achieve neutral NPV after 5 years.

The outcome shown in Table 8 was achieved by adding value of electricity for charging and total maintenance cost to the one fifth of initial investment. This value was divided by amount of electricity for discharging (kWh). This procedure was done for each ESS.

Table 8 – Variation of prices of electricity for discharging needed for neutral NPV under scenario 4

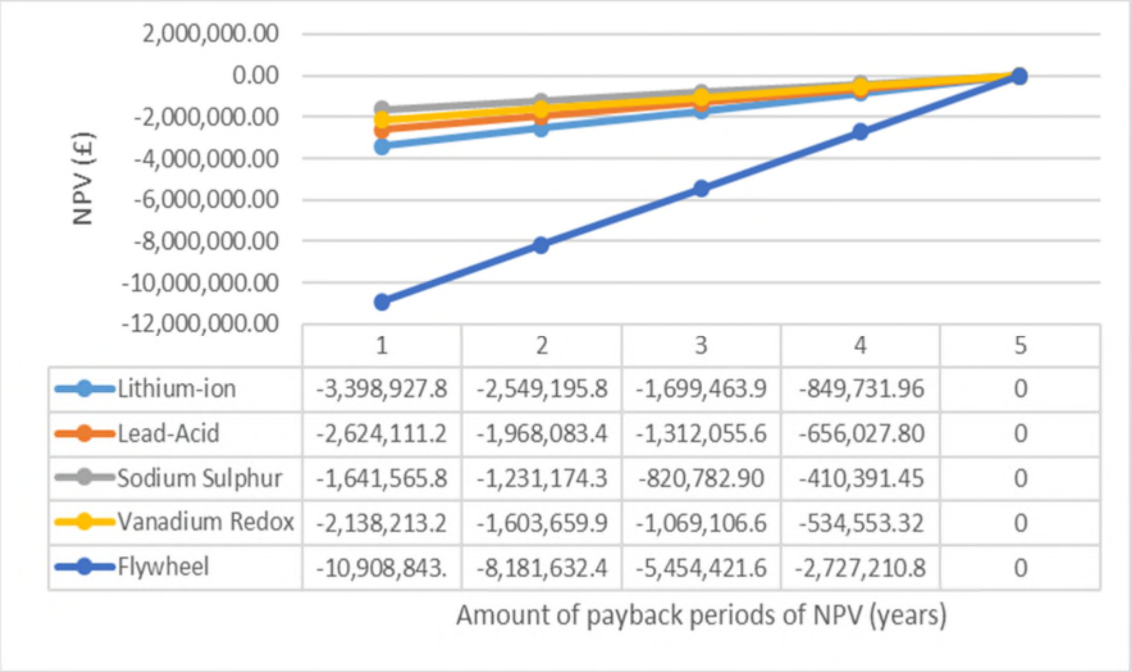
Technology of ESS	Lithium-ion	Lead-Acid	Sodium Sulphur	Vanadium Redox	Flywheel
Needed increase of price of electricity for dischargging (%)	108.32	68.61	26.54	45.58	482.49
Needed price of electricity for discharging (£/kWh)	0.52749	0.42693	0.32040	0.36862	1.47493

Source: Author's work

Table 8 shows prices of electricity which would have to be applied in order to reach at least zero value of NPV after 5 years (Scenario 4 conditions). The lowest value (0.3204 £/kWh) is 26.54% higher and the highest value (1.5793 £/kWh) is 482.49% higher than current price (Rate 1, Table 5).

Figure 9 below displays NPV outcomes under Scenario 4 conditions.

Figure 9 - Scenario 4



	1	2	3	4	5
Lithium-ion	-3,398,927.8	-2,549,195.8	-1,699,463.9	-849,731.96	0
Lead-Acid	-2,624,111.2	-1,968,083.4	-1,312,055.6	-656,027.80	0
Sodium Sulphur	-1,641,565.8	-1,231,174.3	-820,782.90	-410,391.45	0
Vanadium Redox	-2,138,213.2	-1,603,659.9	-1,069,106.6	-534,553.32	0
Flywheel	-10,908,843.	-8,181,632.4	-5,454,421.6	-2,727,210.8	0

Source: Author's work

Figure 9 demonstrates how increased prices of electricity for discharging increased the yearly repayments.

4.4.5 Scenario 5

It was decided to determine how much the initial investment would have to be decreased by, (keeping all other variables the same) to achieve neutral NPV after 5 years.

The outcome shown in Table 9 was achieved by subtracting the sum of recorded cash flows (for 5 years) from initial investments. This value was further divided by a 1% value of the original initial investment. This procedure was done for each ESS.

Table 9 – Decrease of value of initial investment according to scenario 5

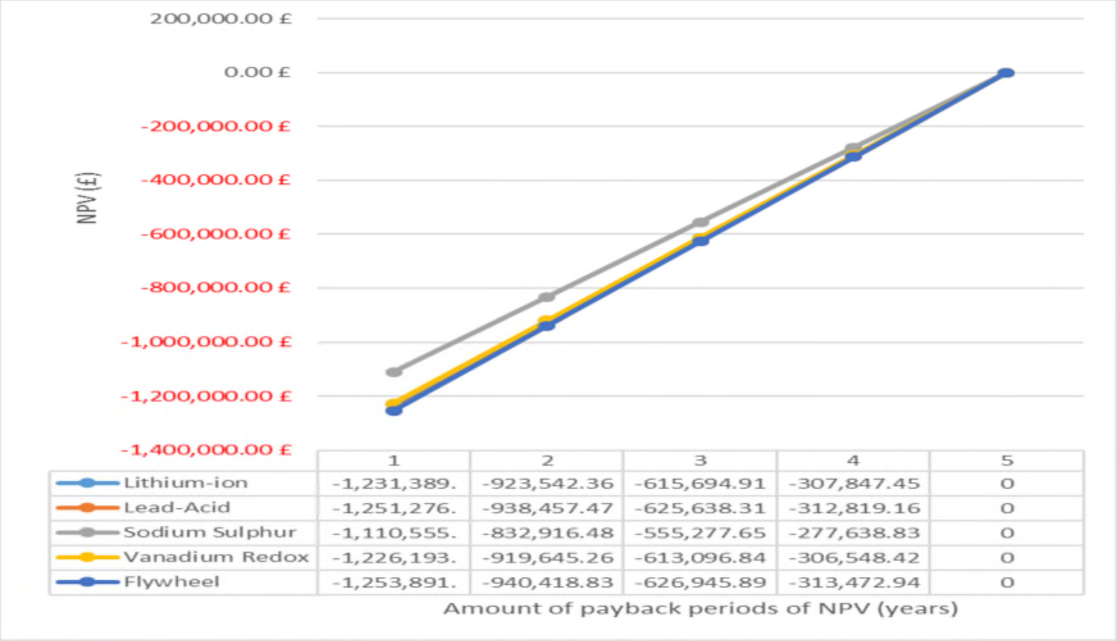
Technology of ESS	Lithium-ion	Lead-Acid	Sodium Sulphur	Vanadium Redox	Flywheel
Decrease of Initial cost (%)	63.77	52.32	32.35	42.65	88.51
Decreased value (£)	1 539 237.27	1 564 095.78	1 388 194.14	1 532 742.09	1 567 364.71

Source: Author's work

Table 9 shows the percentage decrease of initial investment which would have to be applied in order to reach at least a zero value of NPV after 5 years (under Scenario 5 conditions). The decreased values are equal to the positive value of the net present value in Table 7. The lowest decrease is 32.35%, the largest decrease is 88.51% of original value (see Table 4).

Figure 10 below displays NPV outcomes under Scenario 5 conditions.

Figure 10 - Scenario 5



	1	2	3	4	5
Lithium-ion	-1,231,389.	-923,542.36	-615,694.91	-307,847.45	0
Lead-Acid	-1,251,276.	-938,457.47	-625,638.31	-312,819.16	0
Sodium Sulphur	-1,110,555.	-832,916.48	-555,277.65	-277,638.83	0
Vanadium Redox	-1,226,193.	-919,645.26	-613,096.84	-306,548.42	0
Flywheel	-1,253,891.	-940,418.83	-626,945.89	-313,472.94	0

Source: Author's work

Figure 10 indicates how decreased initial investments increased the speed of payback.

Above conducted scenarios (1-5) reveals importance of initial investment as the dominant variable, followed by length of evaluation and price of electricity either for charging or discharging.

5 Discussion

Analysis of electricity consumption within the Cranfield University campus, allowed for the determination of optimal capacity and power parameters of an energy storage system. Analysis was based on historical data about electricity use, provided by Facility office of CU. The optimal values were 5 412.85kWh for capacity and 902.14kW for power. These values were later adjusted due to the efficiency characteristics of technologies (see Table 1), adjusted extended capacity and power of each ESS (as seen in Table 2).

It is possible to say that author underestimated difficulties related to data acquisition from existing UK based ESS as well as information requests to the industrial producers and some information requests to the Facility office of Cranfield University. These difficulties were related to both the willingness of the above-mentioned and the confidentiality of the data. It should be pointed out, that the lack of records about Triad charges might significantly influence final results as well as any missing data about planned renewable sources of electricity deployed within the campus.

Conducted net present value evaluation and sensitivity analysis allow for the conclusion that, operationally, all ESS are profitable, however, due to high initial investments, none of the ESS are likely be accepted as an investment under current conditions.

This statement is in line with findings of Dufo-López and Bernal-Agustín (2015), who focused on Lithium-ion and Lead-acid battery economic simulation, scaled for commercial, industrial (similar to CU) or residential purposes. The study concluded that dependency on the high initial cost of both types of batteries does not allow, under their specific conditions, profitable existence, as was found in this thesis (see Table 9).

However, thesis results about Sodium Sulphur, Lithium-ion and Lead-acid batteries are in contradiction with findings on Yan *et al.* (2014), which conclude that Lead-acid batteries hold more economic expectation than Sodium Sulphur and Lithium-ion, meanwhile this paper prioritises Sodium Sulphur over Vanadium Redox flow batteries, followed by Lead-acid and Lithium-ion batteries.

Masebinu *et al.* (2017) found that the output of sensitivity analysis of the price of electricity used for discharge, prioritises the same battery type as this theses analysis, the output of Sodium Sulphur ESS. The next best positions are Li-ion and Lead-acid battery for Masebinu’s paper and Vanadium Redox, Lead-acid, Li-ion and Flywheel for this paper. The extremely high initial cost of flywheel technology disqualifies it from comparison with other ESS.

Scenario 4 and 5 suggests what input variables to use and how they have to be modified, to allow technologies be at least financial viable under set conditions.

Economic assessment proved the unattractiveness of chosen energy storage systems from a financial point of view but did not consider the positive externalities provided by them such as the balance of the university micro grid, protection from its vital infrastructure and the increase in energy security or carbon reduction as those are subject to a different personal opinion.

6 Conclusion and recommendations

A calculation of the optimal capacity and power, based on data analysis of long-term, seasonal and daily electricity needs of Cranfield University found optimal technical parameters. These parameters are 5 412.85kWh for capacity and 902.12kW for power and might be used by the Facility office of Cranfield University as a basis for further progress in the field of electricity self-sufficiency.

Under current conditions, it does not seem to be financially feasible for Cranfield University to implement an energy storage system within its campus. Unless future development is performed in the production of ESS, which allows for a substantial decrease in the cost of initial investment (see Table 9). Also if Salix Finance changes its funding condition or significantly increases the price of electricity as can be seen in Table 8, none of the considered ESS are economically viable.

Furthermore, NPV calculations can also be used by the Facility office of Cranfield University. The Facility office might implement the estimation of Triad charges, based on their historical data, into their calculations. The calculation could also be made more accurate by incorporating the change in the price of electricity over time, which might be observed in the trend analysis of electricity rates. By involving costs related to disposal, analysis would become a life cycle cost analysis rather than NPV.

Pressure from Government on higher education sector institutions to increase energy efficiency or introduce renewable sources of energy into their energy mix and consequently carbon emission reduction is clear as are the tools which the Government decided to use. Cranfield University needs to keep up to date with different or improved approaches to meet Government plans. This is essential both to avoid penalties stemming from poor plan implementation, and to gain financial and other benefits from good plan implementation.

Within the UK, only Sheffield University installed, with the support of Engineering and Physical Sciences Research council a 2MW Lithium-titanate battery for research purposes (Toshiba Corporation, 2014). The University of Limerick, Ireland installed flywheel hybrid energy storage incorporating Lead/acid batteries as a demonstration project (Power Engineering International, 2015). This shows that there are currently no universities using ESS as a research tool rather than for economic purposes.

REFERENCES

Bank of England (2017) *Bank of England Statistical Interactive Database: Interest & Exchange Rates*. Available at: http://www.bankofengland.co.uk/boeapps/iadb/Rates.asp (Accessed: 1 September 2017).

BEIS (2016) *UK ratifies the Paris Agreement - News stories - GOV.UK*. Available at: https://www.gov.uk/government/news/uk-ratifies-the-paris-agreement (Accessed: 1 September 2017).

Bell, M., Bellamy, O., Gault, A., Hemsley, M., Smith, S., Thompson, M., Barrett, J., Pawar, N., Seera, P., Taylor, S., Westlake, S. and Wildeshaus, S. (2016) *UK climate change following the Paris Agreement*. London. Available at: https://www.theccc.org.uk/wp-content/uploads/2016/10/UK-climate-action-following-the-Paris-Agreement-Committee-on-Climate-Change-October-2016.pdf (Accessed: 1 September 2017).

Board for Energy and Environment (2016) *Annual Environmental Report 2015*. Available at: https://www.cranfield.ac.uk/~/media/files/all_docs/annual-environmental-report-2015-to-2016.ashx?la=en.

Boyle, G. (2012) *Renewable Energy: Power for a Sustainable Future*. 3rd editio. Oxford: Oxford University Press.

Cacuci, D. G., Ionescu-Bujor, M. and Navon, I. M. (2003) ‘Sensitivity and Uncertainty Analysis’, in. Chapman & Hall/CRC Press. doi: 10.1201/9780203911396.ch10.

CU (2011a) *Cranfield University Carbon Management Plan : Progress and amendments*. Available at: https://www.cranfield.ac.uk/~/media/files/all_docs/carbonmanagementplanupdated2010.ashx.

CU (2011b) *Energy Policy*. doi: 10.1093/acrefore/9780190228637.013.174.

DECC (2012) *Planning our electric future: a White Paper for secure, affordable and low-carbon electricity*. Available at: http://www.decc.gov.uk/en/content/cms/legislation/white_papers/emr_wp_2011/emr_w p_2011.aspx%5Cnhttp://linkinghub.elsevier.com/retrieve/pii/S0264410X12014399 (Accessed: 1 September 2017).

Dufo-López, R. and Bernal-Agustín, J. L. (2015) ‘Techno-economic analysis of grid-connected battery storage’, *Energy Conversion and Management*, 91, pp. 394–404. doi: 10.1016/j.enconman.2014.12.038.

European Commission (2010) *Annex 2 - Overview of Europe 2020 Targets*. Available at: http://ec.europa.eu/europe2020/pdf/annexii_en.pdf (Accessed: 1 September 2017).

European Commission (2016) *2020 Climate & Energy Package*. Available at: https://ec.europa.eu/clima/policies/strategies/2020_en (Accessed: 1 September 2017).

Gildemeister (2017) *CellCube FB 200 storage system from GILDEMEISTER energy solutions*. Available at: http://energy.gildemeister.com/en/store/cellcube-fb-200#Technical-data (Accessed: 1 September 2017).

Gitman., L. J. (2005) *Principles of managerial finance*. 11th editi. Boston: Pearson Addison Wesley.

Grothoff, J. M. (2015) *Battery Storage for Renewables : Market Status and Technology Outlook, Irena*. Abu Dhabi: IRENA.

HEFCE (2010a) *Carbon management strategies and plans: A guide to good practice*. Available at: http://www.hefce.ac.uk/media/hefce1/pubs/hefce/2010/1002/10_02.pdf (Accessed: 1 September 2017).

HEFCE (2010b) *Carbon reduction target and strategy for higher education in England*. Available at: http://www.hefce.ac.uk/media/hefce1/pubs/hefce/2010/1001/10_01a.pdf (Accessed: 1 September 2017).

HEFCE (2017) *HEFCE - funded higher education institutions, Higher Education Funding Council for England*. Higher Education Funding Council for England. Available at: http://www.hefce.ac.uk/workprovide/unicoll/heis/#letterC (Accessed: 1 September 2017).

HM Government (2009) *The UK Low Carbon transition plan, Change*. Available at: http://www.decc.gov.uk/ (Accessed: 1 September 2017).

HM Treasury (2016) *Reforming the business energy efficiency tax landscape: response to the consultation*. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/508159/reforming_business_energy_efficiency_tax_response_final.pdf.

HM Treasury (2017) *GDP deflators at market prices, and money GDP: September 2016 (Quarterly National Accounts) - GOV.UK*. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/624527/GDP_Deflators_Qtrly_National_Accounts_June_2017_update.csv/preview (Accessed: 1 September 2017).

Huff, G., Currier, A. B., Kaun, B. C., Rastler, D. M., Chen, S. B., Bradshaw, D. T. and Gauntlett, W. D. (2013) *DOE/EPRI 2013 electricity storage handbook in collaboration with NRECA*. Albaquerque: Sandia National Laboratories. doi: SAND2013-5131.

Larrabee, D. T. and Voss, J. A. (2012) *Valuation Techniques - Discounted Cash Flow, Earnings Quality, Measure of Value Added, and Real Options*. John Wiley & Sons, Inc.

Mahlia, T. M. I., Saktisahdan, T. J., Jannifar, A., Hasan, M. H. and Matseelar, H. S. C. (2014) ‘A review of available methods and development on energy storage; technology update’, *Renewable and Sustainable Energy Reviews*. Elsevier, 33, pp. 532–545. doi: 10.1016/j.rser.2014.01.068.

Masebinu, S. O., Akinlabi, E. T., Muzenda, E. and Aboyade, A. O. (2017) ‘Techno-economics and environmental analysis of energy storage for a student residence under a South African time-of-use tariff rate’, *Energy*, 135, pp. 413–429. doi: 10.1016/j.energy.2017.06.118.

Parliament of the United Kingdom (2008) *Climate Change Act 2008*, *HM Government*. doi: 10.1136/bmj.39469.569815.47.

Power Engineering International (2015) *First flywheel hybrid energy storage plant in Europe is opened*. Available at: http://www.powerengineeringint.com/articles/2015/12/first-flywheel-hybrid-energy-storage-plant-in-europe-is-opened.html (Accessed: 1 September 2017).

Salix Finance (2017a) *Home | Salix Finance*. Available at:

https://www.salixfinance.co.uk/ (Accessed: 1 September 2017).

Salix Finance (2017b) *Schools Energy Efficiency Loans Application Notes*. Available at: https://www.salixfinance.co.uk/system/public_files/england_-_application_notes_june_2017.pdf (Accessed: 1 September 2017).

Tesla (2017) *Powerpack | Commercial and Utility Energy Storage Solutions*. Available at: https://www.tesla.com/en_GB/powerpack?redirect=no (Accessed: 1 September 2017).

The Electric Power Research Institue (2016) *Program on Technology Innovation: Microgrid Implementations: Literature Review 2016*. Available at: https://www.epri.com/#/pages/product/000000003002007384/.

Toshiba Corporation (2014) *Toshiba : Press Release (24 Jun, 2014): Toshiba to Supply Lithium-Titanate Battery for 2MW Energy Storage System Project in UK Led by the University of Sheffield*. Available at: https://www.toshiba.co.jp/about/press/2014_06/pr2401.htm (Accessed: 1 September 2017).

U.S. Department of Energy (2011) *DOE Microgrid Workshop Report, Office of Electricity Delivery and Energy Reliability Smart Grid R&D Program, San Diego, California*. Available at: http://energy.gov/sites/prod/files/Microgrid Workshop Report August 2011.pdf.

UNFCCC. Conference of the Parties (2015) *Paris Climate Change Conference-November 2015, COP 21, Adoption of the Paris Agreement. Proposal by the President.* doi: FCCC/CP/2015/L.9/Rev.1.

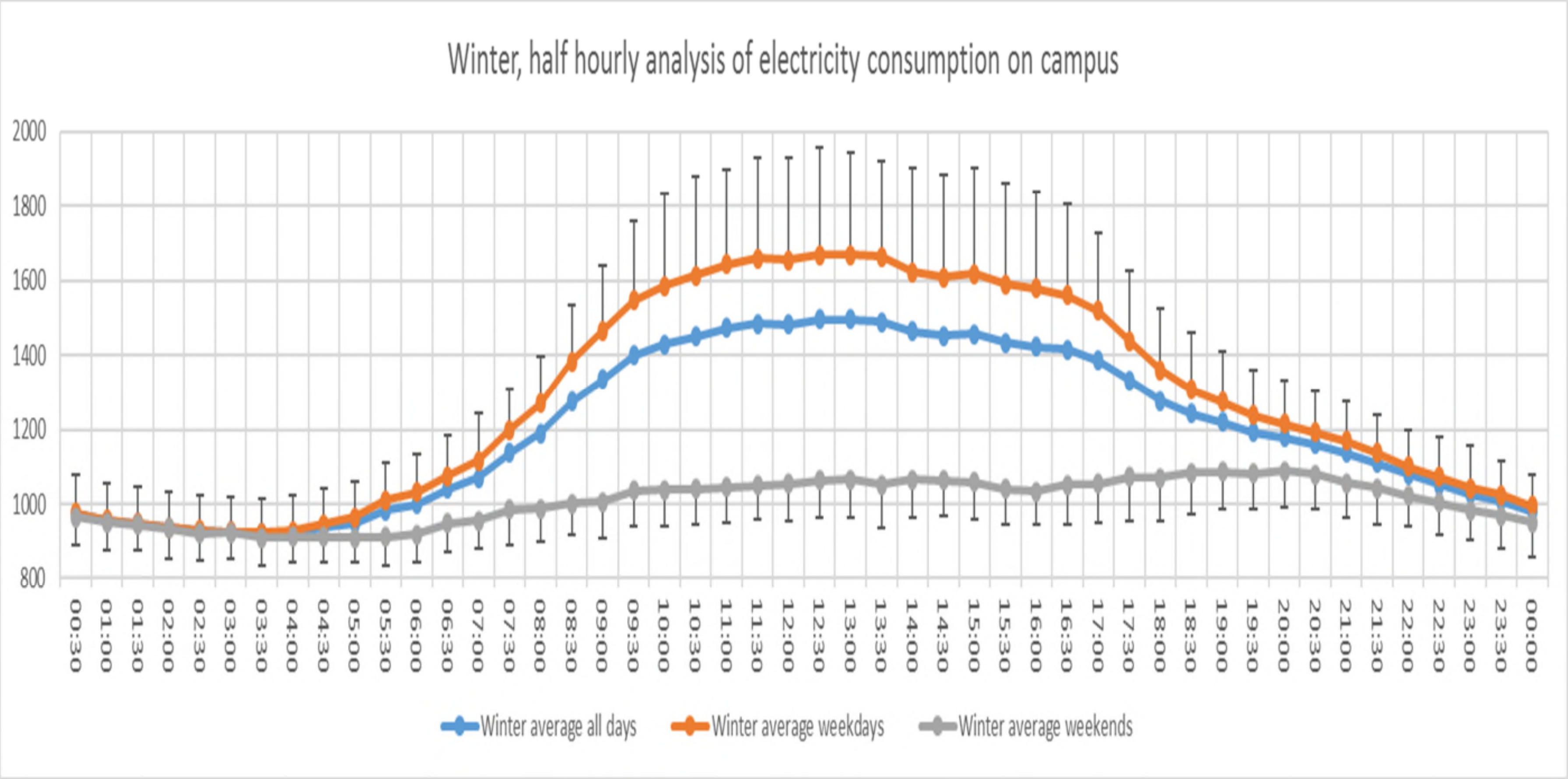
WEC (2013) *World Energy Trilemma: 2013 Energy Sustainability Index*. Available at: www.worldenergy.org (Accessed: 1 September 2017).

Yan, X., Zhang, X., Chen, H., Xu, Y. and Tan, C. (2014) ‘Techno-economic and social analysis of energy storage for commercial buildings’, *Energy Conversion and Management*. Elsevier Ltd, 78, pp. 125–136. doi: 10.1016/j.enconman.2013.10.014.

Zakeri, B. and Syri, S. (2015) ‘Electrical energy storage systems: A comparative life cycle cost analysis', *Renewable and Sustainable Energy Reviews*. Elsevier, 42, pp. 569–596. doi: 10.1016/j.rser.2014.10.011.

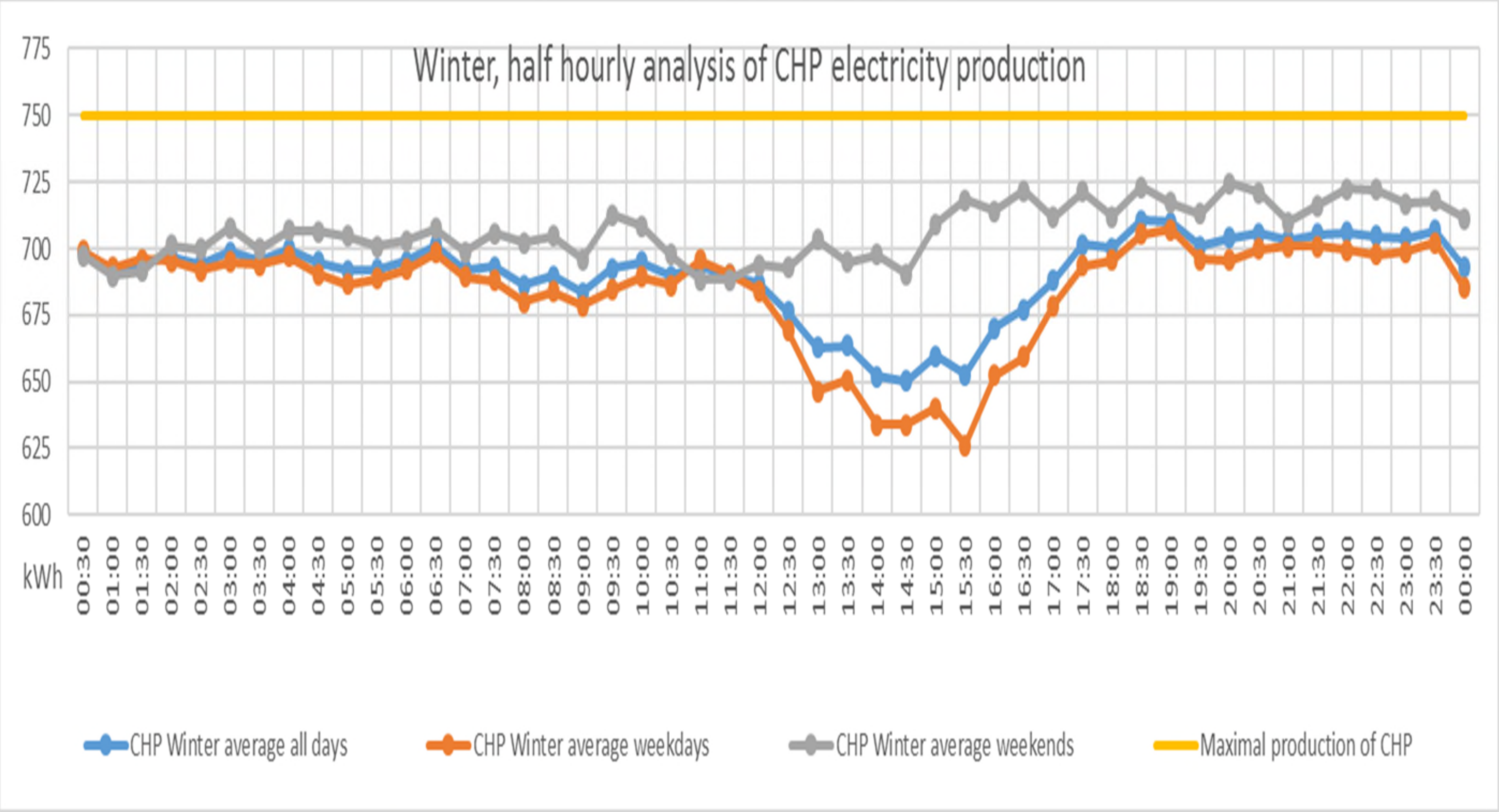
APPENDICES:

Appendix A



Source: Facility office of CU, Author’s work

Appendix B



Source: Facility office of CU, Author’s work

Appendix C

Table 2 - Calculation of extended technological parameters

Technology of ESS	Lithium-ion	Lead-Acid	Sodium Sulphur	Vanadium Redox	Flywheel
Capacity (kWh)	5,412.85	5,412.85	5,412.85	5,412.85	5,412.85
Power (kW)	902.14	902.14	902.14	902.14	902.14
Efficiency (%)	0.88	0.89	0.75	0.88	0.90
Extended capacity (kWh)	6,150.97	6,081.85	7,217.13	6,150.97	6,014.28
Extended power (kW)	1,025.16	1,013.64	1,202.85	1,025.16	1,002.38

Source: Author's work

Table 3 - Salix Finance conditions

Discount rate (%)	0.00
Number of payback periods (years)	5.00

Source: Salix finance

Table 4 - Initial investment calculation

Technology of ESS	Lithium-ion	Lead-Acid	Sodium Sulphur	Vanadium Redox	Flywheel
Power Conversion System (£/kW)	366.68	299.36	289.86	388.07	227.30
Storage Section (£/kWh)	629.62	489.44	236.01	369.85	2229.40
Power Conversion System (£)	375,908.38	303,448.84	348,661.11	397,829.60	227,836.38
Storage Section (£)	3,872,751.40	2,976,690.16	1,703,296.15	2,274,936.99	13,408,217.71
Initial investment (£)	**4,248,659.78**	**3,280,139.00**	**2,051,957.26**	**2,672,766.59**	**13,636,054.09**

Source: Author's work

Table 5 - Variation in electricity prices by different daytime period

Rate	Rate 1 (Red)	Rate 2 (Amber)	Rate 3 (Green)		Charging/discharging cycles
Time	4pm -7pm	7am - 4pm	7 pm - 7am		365
Price (£/kwh)	0.25321	0.10123	0.08321		

Source: Facility office of CU

Table 6 - Cash flow calculation

Technology of ESS	Lithium-ion	Lead-Acid	Sodium Sulphur	Vanadium Redox	Flywheel
Electricity for discharging (kWh)	1,975,690.25	1,975,690.25	1,975,690.25	1,975,690.25	1,975,690.25
Value of electricity for discharging (£)	500,264.53	500,264.53	500,264.53	500,264.53	500,264.53
Electricity for charging (kWh)	2,245,102.56	2,219,876.69	2,634,253.67	2,245,102.56	2,195,211.39
Value of electricity for charging (£)	186,814.98	184,715.94	219,196.25	186,814.98	182,663.54
Maintenance (£/kW -yearly)	5.46	2.69	2.85	6.73	4.12
Maintenance (£)	5,602.09	2,729.43	3,429.45	6,901.13	4,128.05
Net Cash Flow	**307,847.45**	**312,819.16**	**277,638.83**	**306,548.42**	**313,472.94**

Source: Author's work

Table 7- Net presen value calculation

Technology of ESS	Lithium-ion	Lead-Acid	Sodium Sulphur	Vanadium Redox	Flywheel
Cash flow 1.st year (£)	307,847.45	312,819.16	277,638.83	306,548.42	313,472.94
Cash flow 2.nd year (£)	307,847.45	312,819.16	277,638.83	306,548.42	313,472.94
Cash flow 3.rd year (£)	307,847.45	312,819.16	277,638.83	306,548.42	313,472.94
Cash flow 4.th year (£)	307,847.45	312,819.16	277,638.83	306,548.42	313,472.94
Cash flow 5.th year (£)	307,847.45	312,819.16	277,638.83	306,548.42	313,472.94
Initial Investment (£)	-4,248,659.78	-3,280,139.00	-2,051,957.26	-2,672,766.59	-13,636,054.09
Net Present Value (£)	**-2,709,422.51**	**-1,716,043.22**	**-663,763.12**	**-1,140,024.50**	**-12,068,689.38**

Source: Author's work