



**Imperial College  
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## **SUSTAINABLE ENERGY FUTURE**

The Future Cost Projection of Redox Flow Battery

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## Abstract

Because of growing concern over climate change, the increasing demand for grid-connected storage will be anticipated because of the surging growth of intermittent renewable energy system needed to be stabilized. Redox flow battery (RFB), as an electrochemical storage technology that utilizes chemical properties of different electrolytes to reserve and release energy, has huge potential in the future energy market. Its distinctive feature of energy-power decoupling has appealed to R&D institutes to start investigating RFB's feasibility and scalability. However, RFB remains at an early initial stage for large deployment to complement current and newly-existing low-carbon technology. Currently Redox Flow Batteries make up less than 1% of the total battery storage market. With several storage technologies potentially competing for a market that is likely to grow rapidly, it is critical to understand their future costs. However, to this date, there has been relatively few future cost projection analyses of RFBs, and those that have been undertaken are now out of date with regards to their assumptions and cost data.

Therefore, this paper has compiled new lists of component cost inputs from both prior study and experts and deeply investigated the future cost projection of vanadium flow battery (VRFB) by a modified cost bottom-up model. The model is a useful tool of assessing the present and future cost in various hour systems with component cost breakdown, as well as being compatible with stochastic analysis to account for the high uncertainty of VRFB's future cost. The analysis suggested that the cost of 500kW 4-hour VRFB system would fall within a range of 545 to 200 €/kwh in a bimodal distribution with two maxima at 460 and 295 €/kWh which represents the median cost estimate in future conservative and optimistic scenario respectively in normal case; if both mass production of cell stacks and business model of leasing electrolyte happen in the future, that would result in a radical reduction in cost of VRFB which are 313.49 €/kWh and 139.50 €/kWh in future conservative and optimistic scenario, however, regardless of whether these drastic changes might take place, this study indicated VRFB would be the cheapest stationary electrochemical storage system compared to other competitors such as fuel cell and lithium-ion battery.

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## 1. Introduction

For mitigating global warming, the 2015 Paris Agreement gathered the nations to collaborate and limit global temperature rise well below 2 °C above pre-industrial level (Few et al., 2016). To achieve the international climate goal, an inevitably increasing demand for low-carbon power generation technologies has to be satisfied. Vast Investment in the energy sector has been shunted into the new clean technologies such as solar panels, wind turbine, nuclear plants, etc, instead of traditional coal-fired plants since the last two decades, as such, a complex generation mix will be soon expected to supply the grid. However, with such high penetration of these intermittent and inflexible energy sources, the world must create a more flexible electricity system to integrate with renewables as a matter of priority. One way to enhance grid flexibility is to install energy storage in a bid for balancing the intermittency of renewables.

Energy storage involves various forms of conversion. Traditionally speaking, pumped hydropower, hydrogen electrolyser and lead-acid batteries appear as the three most dominant electrical energy storage technologies, currently more than 10 GW/10 GWh deployment over the world respectively(Few et al., 2016); notwithstanding, the public was deeply sceptical about continuing their deployment with emerging renewables. Geographical restrictions curb the use of pump hydropower, renewables are installed in locations where abundant energy sources locate, but not necessarily next to a dam; hydrogen electrolyser or fuel cell still remains expensive; mature but bulky lead-acid battery systems contain harmful and non-environmental friendly materials. These discernible limitations lead to researchers started developing new configurations for energy storage systems(Few et al., 2016).

Redox flow battery (RFB) has presently become one of the candidates that might play a crucial role in enabling the next phase of the energy transition. Along with stabilizing solar and wind output, its millisecond-scale response time and highly power-energy decoupled features would serve as an

incentive for energy storage owners on a wide spectrum of storage applications. The versatile flow battery systems, ideally ranged from minutes, to several hours, to seasonal capacity, would be accordingly deployed into different infrastructures, yet its financial feasibility for a large-scale system is still undetermined due to the relatively immature stage of the technology.

## 1.1 Problem Definition and Motivation

This paper explores how the capital cost of all-Vanadium flow battery (VRFB), as one of the most successfully commercialised RFB, will project in the future. Until now, besides VRFB, zinc-bromine hybrid flow battery with high energy density relative to VRFB also presents an attractive system able to commercialise extensively. Material such as an electrode and bipolar plate, designated for the zinc-bromine system is required to withstand the highly oxidative halogen, also, a special design of membrane is utilized to mitigate the adverse effect of dendrite formation, which rough surface may deform porous structure of a membrane("Zinc-Bromine (ZNBR) Flow Batteries | Energy Storage Association," n.d.). However, with such demanding on component's specification of the zinc-bromine system, prior literature and manufacturing industries provide little information to help identify the component's cost specifically for the system, therefore, the thesis will only focus on all-vanadium flow battery system.

Regarding the cost of VRFB, there is relatively little publicly available data on the cost of VRFB systems, largely due to their limited commercialisation to date, and its future cost is highly uncertain. Discussion regarding VRFB's electro-chemistry have dominated research in recent years, but rarely in evaluating capital cost in a bottom-up approach. EPRI.(2007), Viswanathan et al.(2014) and Noack et al.(2016) had once developed a highly detailed but out-of-date bottom-up models on RFB's capital cost which have brought much attention to both developers and researchers. Nevertheless, the cost of raw materials and battery components which determines and builds up the battery system cost

wildly fluctuates. The necessity of researching up-to-date material information with a bottom-up cost model can indeed attest to VRFB's economic viability on future large-scale deployment. The result would be beneficial in evaluating the possibilities of challenging other storage market's competitors such as Lithium-ion Battery, in the meantime, recognizing what aspects can be improved to return to the global battery race.

## 1.2 Project Outline

The thesis has been organised in the following way. The first section of this paper will thoroughly review the prior literature on the background and components of VRFB, it will then go on to the in-depth investigation in economic perspective on the historical cost of different components of VRFB. The second section will cover the research design, methodology of the bottom-up cost model, and the main model's assumptions. The third section will present and analyse the findings of the research, focusing on scenarios at present, conservative future and optimistic future; demonstrate the dependence of future costs on the energy capacity of RFBs as well as their power output; display the probability of different outcomes about system cost with Monte Carlo Simulation. The remaining part of the paper will proceed to discussion based on the findings and conclusion.

## 2. Background of Vanadium Redox Flow Battery

VRFB is an electrochemical form of energy storage by utilizing chemical interactions which are reduction and oxidation to undergo charge and discharge. Chemical solutions, which are initially prepared by either  $V_2O_5$  or  $VOSO_4$ , are stored in separated external tanks. In figure 1, they are carried by pumps to a reaction chamber where the electrodes and the ion exchange membrane are located. Electrodes connected with an external circuit provides a path for electrons from either side of the chemical ions, depending on the direction of the charge cycle.

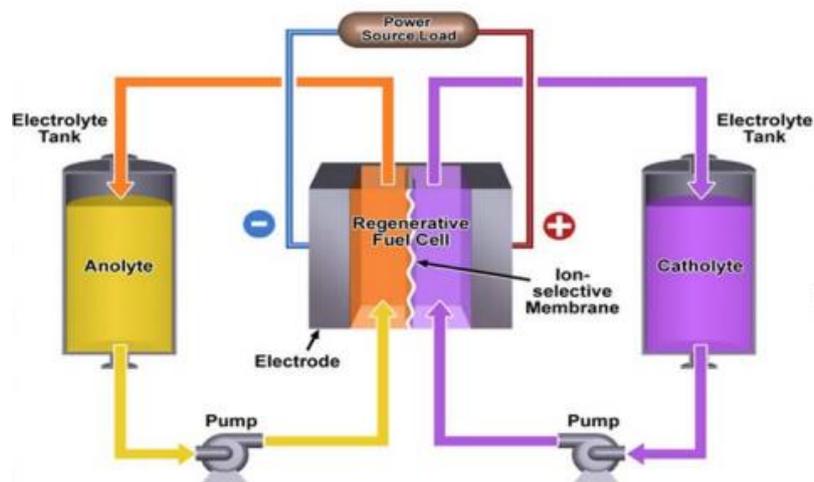


Figure 1 Schematics of Redox Flow Battery(Sprenkle, n.d.)

During the discharging cycle, electrons are extracted by oxidation at the anolyte side and flow from anode to cathode through the external circuit to create a potential difference between terminals. Then, the flowing electrons are accepted by the positive side where the cathode is, ions formed by reduction flow across the exchange membrane in order to maintain charge neutrality. The direction of the electrons and ion flow are reversed when it is charging (Weber et al., 2011). To fully comprehend the situation of VRFB, this section will cover how VRFB developed throughout the history and both the benefits and limitations of VRFB .

## 2.1 History of Redox Flow Battery

Research into redox flow battery has a relatively short history over the past decades. It is not until the late 1980s that the Australians in University New South Wells (UNSW) considered vanadium redox battery (VRFB) worthy of scholarly attention. With serious discussions and analyses of the feasibility of vanadium redox battery, the Australian research team successfully demonstrated the first functional VRFB and its economic viability, leading to an increasing amount of mining programs aimed at exploiting vanadium since the achievement in 1986(Alotto et al., 2014).

Prudent Energy, Sumitomo Electric Industries and Thai Gypsum received the patent license that was sought and filed by UNSW in Australia (Kear et al., 2012) and continued its R&D. To facilitate VRFB deployment, they applied VRFB systems on voltage quality control in wind farm, voltage drop protection in a semiconductor factory, load levelling in an office building, university and golf course's PV system, and stabilization of turbine output in wind turbine(Leung et al., 2012). Up to date, global VRFB project from 2015, which integrated with renewables, is shown below at table 1. Overall, it can be seen that China had the leading position in deploying large-scale VRFB systems, and its scale increased significantly through the years. The latest project in Dalian would be one of the largest system (200MW, 800MWh) in the world, it will be connected to the main grid of Liaoning Province and renewables to form a bulk energy supplying centre and stabilize the grid (Weaver, 2017).

| <b>Project</b>   | <b>Location</b>            | <b>Operation Date</b> | <b>Power Rating(kW)</b> | <b>Duration (hr)</b> |
|--|----------------------------|-----------------------|-------------------------|----------------------|
| University of New South Wales 30 kW / 130 kWh ESS                    | New South Wales, Australia | Jun 01, 2015          | 30                      | 4.2                  |
| Lausanne Polytechnic School-Martigny-200kW                           | Valais, Switzerland        | Oct 05, 2015          | 200                     | 2                    |
| redT Energy Storage Wokingham Development Facility 5 kW / 40 kWh ESS | Berkshire, United Kingdom  | Oct 15, 2015          | 5                       | 8                    |

|  |                                 |              |         |    |
|--|---------------------------------|--------------|---------|----|
| The Zhangbei Project - State Grid /<br>Sparton Resources | Hebei, China                    | Jan 23, 2016 | 2000    | 4  |
| Busselton Farm Property - VSUN Energy<br>Pty Ltd         | Western Australia,<br>Australia | Sep 13, 2016 | 10      | 10 |
| Dalian VFB - UET / Rongke Power                          | Dalian, Liaoning,<br>China      | Dec 31, 2018 | 200,000 | 4  |

Table 1 Recent installation of VRFBs for various applications (“DOE Global Energy Storage Database,” n.d.)

Until now, various types of redox flow battery are still under investigation on the possibility to supersede VRFB for a large scale of cheap deployment. In figure 2, the two most commercialised battery, VRFB and ZBFB, utilize inorganic redox materials in aqueous electrolyte. Within the same aqueous category, Yang et al. (2016) introduced a new and high-performance organic flow system with quinone-based redox couples, this configuration could avoid the use of heavy metal like vanadium or zinc with organic matters from an inexpensive and fast replicated biological process. For non-aqueous electrolyte, Sleightholme et al (2011) had investigated on a metal-ligand setup of manganese acetylacetonate electrolyte, yet it showed less competitive than VRFB due to the low cell potential of 1.1 V; while organic active species in the non-aqueous electrolyte, on the contrary, offers several interesting opportunities. It provides a large choice of redox couples for both positive and negative sides; the solubility and electrochemical properties of electrolyte are easily tunable by modifying their chemical structure with the simple synthetic pathway. These advantages bring a more stable manipulation of voltage and energy density while operating despite an expensive cost on the solvent.(Perry and Weber, 2016) More and more new experimental setups for redox flow system will be anticipated, nevertheless, speaking of large-scale deployment, there is still a long way to go.

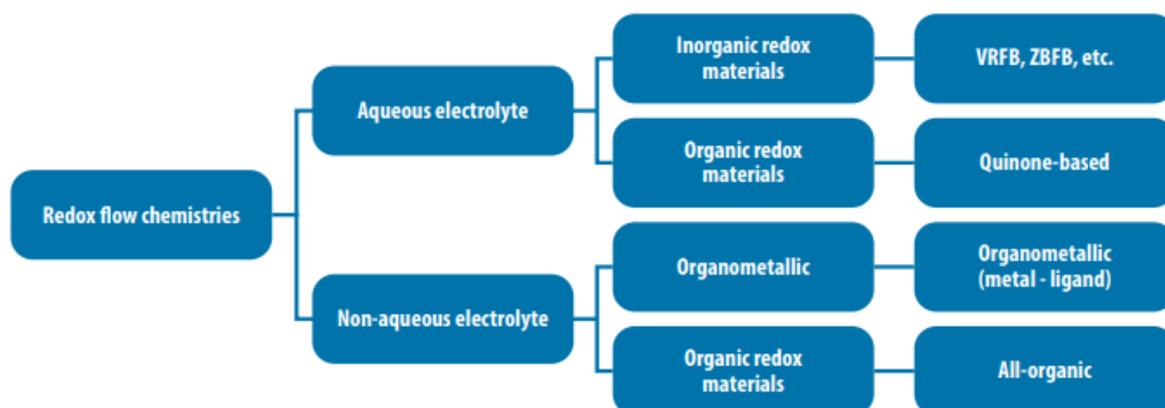


Figure 2 Different Type of Redox Flow Battery (“Electricity storage and renewables: Costs and markets to 2030,” 2017)

## 2.2 Benefits of Vanadium Redox Flow Battery

| Benefits  | Description   |
|---|---|
| <i>Decoupling Energy and Power</i>                | The decoupled feature of its scalability allows to scale up energy capacity by installing larger tanks for electrolytes and power capacity with more stacks of cells. The flexibility enables to meet different application, for example, energy time shift in bulk energy supply, load following for ancillary service and power quality controls for renewables (Choi et al., 2016; Doughty et al., 2010; Gong et al., 2015; L. Li et al., 2011; Moore et al., 2015; Weber et al., 2011; Xu et al., 2011; Zhao et al., 2015). |
| <i>High reversibility</i>                         | Thorough reversibility of the charging and discharging processes enables RFB to operate by merely changing oxidation states of metal ions without consuming any substance during the reaction (Alotto et al., 2014; Weber et al., 2011).  |
| <i>Low Self-Discharge</i>                         | RFB can minimize the occurrence of internal chemical reactions like a lead-acid battery or other storage types such as compressed air energy storage and flywheel because electrolytes are stored in external tanks. The battery can remain idle for a long time without energy loss (L. Li et al., 2011).  |
| <i>High Cycle Life</i>                            | RFB presents a tremendously high number of cycle life around 10000 hours with high round-trip efficiency (Choi et al., 2016; L. Li et al., 2011; Xu et al., 2011; Zhao et al., 2015).   |
| <i>Simple Mechanism on Temperature Regulation</i> | To reach the operating temperature does not require auxiliary heating, instead, it can be done with the exothermicity of the reaction by regulating the flow of electrolyte (Weber et al., 2011).   |
| <i>Environmental-friendly</i>                     | RFB has a low polluting potential of vanadium compared to lead-acid benefits from pollution-free operation (Doughty et al., 2010; Kear et al., 2012; Zhao et al., 2015).  |
| <i>Fast Response Time</i>                         | The RFB’s response time is scaled in milliseconds, and which suits lots of grid applications (“Electrical energy storage for mitigating climate change,” 2016).   |

Table 2 Strengths of Vanadium Flow Battery

## 2.3 Previous Research on limitation to facilitate VRFB's deployment

### *Low Power Density*

However, due to its low power density, VRFB is not applicable for mobile appliances like cell phones and still takes time to compete Lithium-ion battery in this market. Several studies highlight the increase of power performance could be achieved by adopting different redox-active species such as non-aqueous lithium-ion couple, solid oxide RFB with closed-loop hydrogen circulation and non-aqueous zinc-iron couple (Gong et al., 2015; Xu et al., 2011; Zhao et al., 2015). If researchers intend to optimise VRFB's energy density, much more fundamental chemistry study via experimental and computational approach is required. Weber et al. (2011) had identified several important aspects that are necessarily investigated deeply: Charge transport and electrochemical reaction at and near both the electrode surface, active species crossover in the membrane, coordination of active species and "spectator additive molecules/ion" and fluid monitoring within the cell architectures.

### *Vanadium Ion Precipitation*

Also, VRFB originally has a narrow range of operating temperature from 15°C to 35°C. When the system exceeds the temperature it supposes to be, either vanadium ion starts precipitating at the bottom of the tank, resulting in electrolyte imbalance and capacity loss. Therefore, an extra cost for external temperature regulator might be necessarily installed to maintain the temperature within the cell (Choi et al., 2017; Weber et al., 2011). Parasuraman et al. (2013) reviewed the importance of supporting electrolyte in determining the solubility or stability of vanadium ion in different oxidation state and identified concentrated sulfuric acid is currently the best agent to increase hydrogen ion's concentration, as well as the solubility of  $V_2O_5$  by forming vanadium sulfate. This observation has successfully broadened the temperature operating range from 10 to 50 degrees Celsius, loosening the high requirement of control system. More recently, with a combination of sulfate and chloride electrolyte, Li et al. (2011) have significantly facilitated the reduction of RFB's operating cost by

widening the temperature window of -5 to 50 degrees Celsius that RFB's electrolyte could remain stable.

### *Expensive Components*

RFB requires its high-quality components as a result of high capital cost. A detailed cost sensitivity analysis on RFB developed in Viswanathan et al. delves into the effect on total cost by different component's cost. He demonstrates the RFBs' cost breakdown in various Energy to Power ratio(E/P), which is also known as operation duration in hour. The electrolyte comprises more than a half of the total cost in high E/P ratio system while power's components such as membranes, pumps and electrodes dominate in the total cost in low E/P setting. In order to reduce cost in components, a prior study has presented the feasibility of replacing an all-vanadium couple with cheap redox-active couples; optimizing manufacturing processes of component's production. A more detailed discussion on component's cost will be carried on in a later section of economic perspective on VRFB (Chang et al., 2016; Gong et al., 2015; Lee et al., 2017; X. Li et al., 2011; Milshtein et al., 2017; Minke et al., 2016; Minke and Turek, 2015; Shin et al., 2013).

### 3. Major Components of Redox Flow Battery

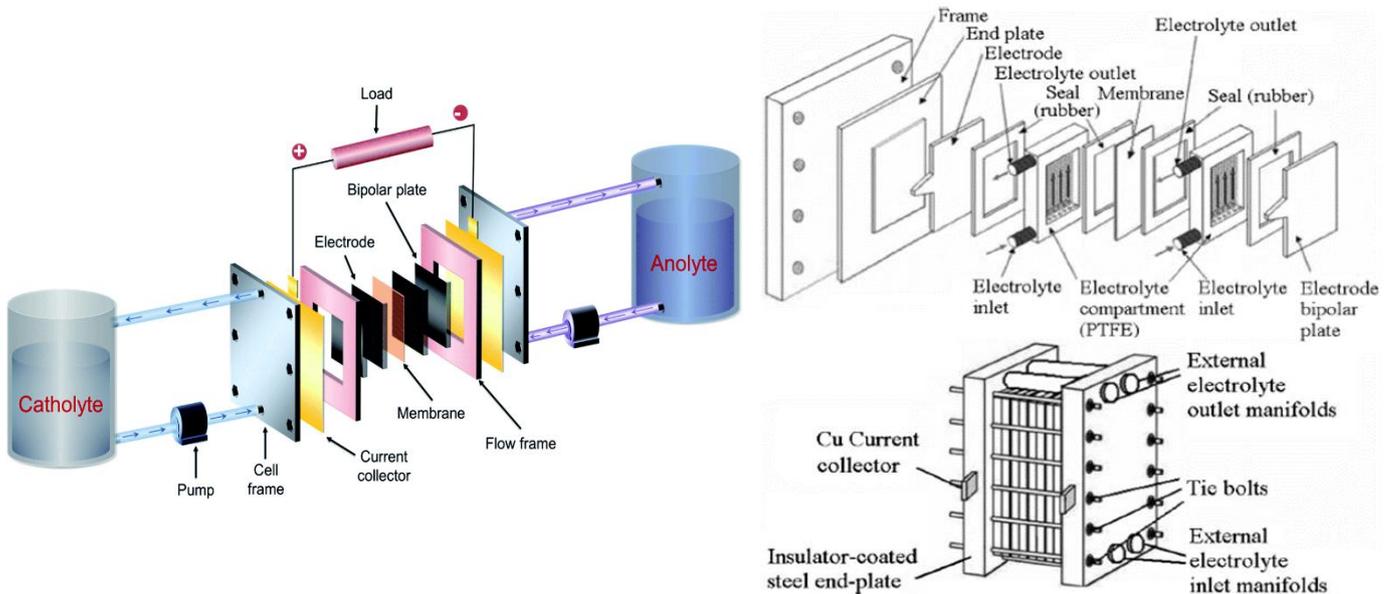


Figure 3 Explosion View of Redox Flow Battery and Components of a Flow Unit Cell and a Battery Stack(Kim et al., 2014; Leung et al., 2012)

A VRFB single cell has a sandwich-like structure, assembled by multiple plain layers with various material which the section will later discuss individually. This efficient design helps to pile cells in series to build a cell stack, combining individual cell's voltage to a larger output. The system can achieve a larger power output with the repeating cell stack unit. These cell stacks are connected to two storage tanks full of electrolytes. When it is charging/discharging, pumps are powered to circulate the liquid to cell stack's manifolds, then the electrolytes are diverted to every cell's felt electrode to undergo electrochemical reactions. The charge is balanced via cross-flow mechanism at a membrane, which is compressed in the middle of two felt electrodes, and the charger carrier could be  $H^+$  or anion depending on the nature of the membrane. Meanwhile, current collectors made of copper, which gather electrons from every single cell, are situated at the two ends of the stack to power the load.

Every vanadium flow system consists of part which either scale with power rating or energy capacity, known as power component or energy component. Cell stack's unit such as ion exchange membrane and auxiliary system like fluid regulation system, power conversion system and control system serve as power components; while vanadium active species, electrolyte and tank are considered as energy components.

### 3.1 Ion Exchange Membrane

The major purpose of having Ion exchange membrane sitting in the middle of electrodes as resistance and separating anolyte and catholyte inside the cell unit is to avoid mixing of electrolyte leading to self-discharge and cell capacity irreversible loss while letting charge carrier complete the circuit (EPRI.(2007)) .It allows  $H^+$  (aqueous electrolyte) or  $BF_4^-$  and  $PF_6^-$  (non-aqueous electrolyte) flowing through to balance the system's charge(Shin et al., 2013; Weber et al., 2011). The table below shows the different membrane and their corresponding performances.

| <b>Membrane Type</b>                                     | <b>Performance Description</b>   |
|--|--|
| <i>Daramic + Divinylbenzene (microporous separator)</i>  | A thinner layer of divinylbenzene due to sulfonation leads to lower chemical stability and higher vanadium ions permeability   |
| <i>Nafion (perfluorinated membrane)</i>                  | Crossover of vanadium ions results in a decrease in energy efficiency. A costly modified Nafion membrane can help improve performance                                      |
| <i>Other Perfluorinated Membrane(PVDF as Backbone)</i>   | Higher performance than Nafion 117 in terms of permeability and conductivity, potential challengers in membrane market synthesized by the cheap solution-grafting method   |
| <i>Non-Fluorinated Membrane</i>                          | Low cost, excellent mechanical and chemical stability and high ion selectivity, but structure may be decomposed with highly concentrated sulphuric acid in the electrolyte |
| <i>Other Hydrocarbon Based Cation Exchange Membranes</i> | Most of them have comparable performance as Nafion 117 does, but the rise in temperature will increase the permeability of vanadium ions                                   |
| <i>Anion Exchange Membranes(AEM)</i>                     | The improved anion exchange membranes show much lower permeability of vanadium ions and high Coulombic efficiency compared to Nafion 117                                   |

|   |  |
|---|--|
| <i>Amphoteric Ion Exchange Membrane</i> | Fabricating with radiation grating, the amphoteric ion exchange membrane has better performance than Nafion 117 in the perspective of permeability, proton conductivity and OCV decay. |
|---|--|

Table 3 Evaluation of Ion-Exchange Membrane (Prifti et al., 2012)

Maria Skyllas-Kazacos, well-known as the inventor of VRFB, had also attested the excellent and long last chemical stability of Nafion membrane in spite of the swelling phenomenon (Parasuraman et al., 2013), which speculation is coherent to the result of an accelerated aging test in  $\text{VO}_2^+$  from The Chemours Company, one of the manufacturers of Nafion membrane in the USA. Between Nafion and anion exchange membrane (AEM), Nafion membrane cannot be oxidized by vanadium electrolyte; while AEM has a greater potential to degrade due to the loss of side-chain function group ("Nafion™ membranes - Delivering on the Promise of Clean Energy," n.d.).

Manufacture process of ion exchange membrane varies with types. Recently, three of the most prevailing membranes: Nafion, SPEEK and Nanofiltration membrane (NFM) has been evaluated in terms of synthesis and cost. (Minke and Turek, 2015) The five raw materials involved in the Nafion synthesis include tetrafluoroethylene (TFE), sulphur trioxide ( $\text{SO}_3$ ), hexafluoropropene (HFP), sodium hypochlorite (NAOCl) and sodium hydroxide (NaOH). The later four chemicals undergo a series of complex chemical reactions and purification to form a co-monomer called PSEPVE, then PSEPVE polymerizes with TFE to produce Nafion.

An alternative ion-exchange membrane, sulfonated poly ether-ether-ketone membrane (SPEEK) requires more initial raw materials, the less complicated manufacturing process reduce the overall cost of the membrane though and its total membrane cost is relatively lower than Nafion. Cost advantages on fewer raw materials requirement and involving cheaper mechanical extrusion and calendaring process for membrane synthesis, NFM presents the lowest cost potential among the three candidates.

## 3.2 Electrode

High surface area carbon felt electrodes are used in one of the most commercialized RFB, vanadium flow battery. The felt-electrode take advantages of both cost and performance of using carbon as a raw material. Cheap carbon brings chemical stability to the component in avoidance to react with acidic electrolyte to produce hydrogen during operation (EPRI.,2007). However, Parausman et al.(2013) identified that when a cell unit is overcharged, oxygen evolution from carbon electrode would be observed because the strong oxidizing agent in electrolyte oxidize and disintegrate carbon electrode. Any gas evolution from cell components is detrimental to the stability of cell architecture and its output performance, thus, a functionally accurate control system plays a crucial role in the operation to prevent the cell from excessive overcharge.

Synthesizing a piece of carbon felt with high electrical conductivity, high specific surface area and high permeability for redox-active electrolyte have a high dependency on manufacturing steps (Minke et al., 2017). Raw materials either plant's cellulose or propylene from fossil fuel are chemically processed to viscose fibre (Rayon) or acrylic fibre (PAN), and the fibres continue to undergo a crucial dehydrated sizing procedure to matting fibres together. Then, it is followed by a series of thermal treatment to carbonization (Minke et al., 2017). The sizing procedure greatly determines electrical resistance, porosity and surface mechanical strength of the felt, thus, the operator needs to be concerned about parameters such as a number of needles which are used to knit the carbon felt, needle's direction, puncture frequency and line speed. Carbon content in the felt reaches 99%, precious metals such as niobium and ruthenium are often added to ameliorate electrode's performance (EPRI,2007). Between the Rayon and Pan-based carbon felt, an in-depth comparison had been drawn by (Zhong et al., 1993). They pointed out that, attributed to rayon's microcrystalline structure, it was outperformed by Pan-based in terms of electrical conductivity and ability of resisting oxidation.

SGL group and Mersen are two of the largest manufacturer supplying RFB companies with both Rayon and PAN types carbon felt (“Battery felts and bipolar plates for redox flow batteries | SGL CARBON,” n.d.).

### 3.3 Reactor Components: Bipolar Plate, Gasket and frames

Each redox active cell is physically held by a pair of carbon bipolar plates, end plates and a number of gasket plates (Ha and Gallagher, 2015). The bipolar plate is designed for connecting cells in series into a stack, it exhibits high electrical conductivity to conveying electrons and corrosion resistance to acidic electrolyte environments. Improvements in mechanical strength and conductivity have been progressively achieved since the 1990s, it involved experiments with a range of bipolar substrates, for instance, polyethylene matrix, rubber and plain polymer sheet (EPRI. 2007).

The conventional bipolar plate consists of multiple components and brings about time and cost consuming manufacturing process (Chang et al., 2016). Several papers have revealed new epoxy composite bipolar plate’s design in a more integral assembly with better performance (Chang et al., 2016; Kim et al., 2014; Lee et al., 2017). In terms of manufacture, a study features the cost and performance prospect of the composite bipolar plate in RFB with two prevailing processing methods: compression moulding and injection moulding (Minke et al., 2016). Possessing various functions in RFB such as conducting electricity and separating corrosive electrolyte from cells, a functional bipolar plate necessitates high manufacturing requirement which may lead to costly expense. The author creates a baseline scenario to compare the manufacturing cost of the two technologies regard to bipolar plate’s thickness and carries sensitivity analysis on how manufacturers could effectively reduce production cost. The findings confirm injection moulding provide production’s speed and cost advantages over compression. Approaches for mass production such as doubling cavity, shortening

manufacturing cycle time could open high possibilities of reducing much expense on the cost of the composite bipolar plate.

Gaskets and frames are responsible for sealing function of the cell stacks, with a high pressure from the electrolyte, the elastomer material could self-tighten the system to enhance the sealing performance. Each electrode is sandwiched between two rubber gaskets to avoid any contact or short-circuit of electrodes, also during assembling of a cell stack, crack or deformation of an electrode might occur if gaskets are not placed as a buffer under a high mechanical pressure from clamping unit. Some of the experimental and model settings of VRFB used Viton rubber or fluorocarbon gasket for sealing (Minke et al., 2017b), and it is reported that the synthetic rubber material works excellently with its chemical resistance in aggressive media like vanadium electrolyte (“Viton Rubber Gasket | FKM Gasket | Viton Flange Gasket,” n.d.). Little literature had specified about the manufacturing process of gasket especially for vanadium flow battery, but Ha and Gallagher et al (2015) identified both frames and gaskets are manufactured by insert moulding, as one of the specialized plastic injection mouldings.

### 3.4 Redox-Active Material: Electrolyte

Various types of electrolyte present the most important component which determines battery’s power-energy output and stability in different RFB’s system (Pan and Wang, 2015; Ponce de León et al., 2006; Wang et al., 2013; Weber et al., 2011). Commercial-scale all-vanadium redox flow battery (VRFB) consists of vanadium-ion as redox-active species and sulfate anion as speculative balancing ion which possesses a non-poison advantage over halide ion (EPRI.,2007). It features a non-cross contamination property, separating the positive active ion and negative active ions during operation, and which could guarantee a secure capacity and stable conversion efficiency (Choi et al., 2017).

The electrolyte comprises more than a half of the total cost in high E/P ratio system (Viswanathan et al., 2014). Therefore, manufacture of vanadium electrolyte has partly governed the total cost of VRFB. Vanadium electrolytes can be prepared with raw materials, vanadium oxide sulfate ( $\text{VO}_2\text{SO}_4$ ) or vanadium pentoxide ( $\text{V}_2\text{O}_5$ ). Although  $\text{VO}_2\text{SO}_4$  has a higher solubility in favour of avoiding precipitation of vanadium ion, it is way more expensive than  $\text{V}_2\text{O}_5$  (Parasuraman et al., 2013).  $\text{V}_2\text{O}_5$  are extracted from titanomagnetite ore through a complicated process with subsequent pyro and hydrometallurgical process (Choi et al., 2017; Palant et al., 2006). Then, Electrolysis  $\text{V}_2\text{O}_5$  powder with sulfuric acid to these raw materials to produce  $\text{V}^{3.5+}$  is followed by a pre-charging process to complete the whole process.

The cell's performance is highly affected by purity, solubility and temperature stability of the electrolytes. Once precipitation of electrolyte happens, it results in irreversible loss of capacity (Pan and Wang, 2015). Accessing the permeability of electrolyte ion varying with different operating temperature is of paramount importance since ion-crossover through the membrane might happen (Parasuraman et al., 2013). Power loss through shunt current in electrolyte also presents as due to the high ionic conductivity (Choi et al., 2017).

### 3.5 Pump, Tank, electronic and control system

Pump and tank are installed in a large-scale vanadium redox flow battery. These components need to be corrosion resistant to the acidic electrolyte solution in order to have a longer life cycle (EPRI.,2007). Magnetically-driven centrifugal pump is well suited to complement RFB system since a large-scale flow battery comprises more than 100 pumps within the system, maintenance of pump would embed as a time-consuming and problematic issue to the operator, and this type of pump could minimize leakage and impact from maintenance (Adam.Bristow, 2015). Fibreglass tank is utilized for acidic electrolyte's storage, and flow frame made of inexpensive PVC help direct electrolyte to the

redox-active site (EPRI.,2007). Much attention has been drawn about RFB system in pressure loss at piping, shunt loss through flow frame and unnecessary pump energy consumption, and these should be minimized with an optimal configuration (Ma et al., 2012; Tang et al., 2014; Viswanathan et al., 2014).

A typical control system consists of a sensor, actuator and controller. In a flow battery system, the sensors are continuously monitoring the level of state of charge, temperature or voltage; while the controller plays as a cerebrum to decide which operation mode needed to be carried and send a signal to the actuator (pump or heat exchanger) to regulate an operation. In terms of the latest progress on the control system, Kroner et al. (2018) introduced a novel amperometric sensor to monitor the state of charge in a VFB. Unlike the traditional methods such as conductivity test, optical measurement and redox titration, the amperometric method which is suitable for both positive and negative electrolyte could provide an accurate and reliable result through on-line monitoring. Also, Thomas Lueth et al. (2018) from Karlsruhe Institute of Technology has designed an automatic battery management system. The highly integrated system could communicate with the grid operator to obtain high-level information such as local energy demand distribution, then interact with the flow battery system to supply capacity. Power conversion system, which could convert electric energy to either DC or AC, in vanadium flow battery is also as necessary as a control system. Recently, Trumpf Hutterer, one of a power electronics company, presented a study on cooling of a power conversion system for redox flow batteries using the electrolyte, this efficient cooling method may bring down the operating cost in the future (Lothar et al., 2018).

## 4. Economic Perspective of VRFB

This section covers the historical cost implications of VRFB, ranged from single components to the total system. This cost-related information is obtained from previous literature in table 2 and experts or manufacturers who attended The International Flow Battery Forum 2018 in Lausanne, Switzerland.

| Author                 | Year | Power (kW) | E/P    | Active Area m <sup>2</sup> | Current Density mA/cm <sup>2</sup> | SOC Range | Molarity of Vanadium |
|------------------------|------|------------|--------|----------------------------|------------------------------------|-----------|----------------------|
| EPRI                   | 2007 | 250-1000   | 4-8    | -                          | -                                  | 20-80%    | 1.6-2.0              |
| Viswanathan et al      | 2014 | 1000       | 0.25-4 | -                          | 100-300                            | 10-90%    | 1.5-2.5              |
| Darling et al          | 2014 | -          | 5      | -                          | -                                  | 10-90%    | 1.6                  |
| Crawford et al         | 2015 | 1000       | 0.25-4 | 0.149-0.185                | 320                                | 9-91%     | 1.2-2.5              |
| Zeng et al             | 2015 | 1000       | 8      | -                          | 120                                | 15-85%    | 1                    |
| Moore et al            | 2015 | 1000       | 6      | 1                          | 604                                | 20-80%    | 1.6-2.0              |
| Ha and Gallagher et al | 2015 | 20         | 5      | 0.1                        | -                                  | -         | -                    |
| Noack et al            | 2016 | 10         | 12     | 0.058                      | 50                                 | 20-80%    | 1.6                  |
| Milshtein et al        | 2017 | -          | 5      | 0.0811                     | 7.26                               | 10-90%    | 1.5                  |
| Minke et al            | 2017 | 1000-20000 | 4-8    | 2.7                        | 100                                | 20%-80%   | 1.6                  |

Table 4 Conference paper and Journal article related to vanadium flow battery's capital cost/economic models for present & future scenario

### 4.1 Vanadium Flow Battery's cost breakdown

To identify which components are more influential to the total system cost, prior studies generally used a pie chart for displaying data in different categories. A detailed cost breakdown in two VRFB systems with different E/P ratio is shown in figure 9 by Viswanathan et al., (2014). Power-related components such as membrane and control system dominate in low E/P ratio while energy, while energy-related component, electrolyte dominates the total cost in high E/P ratio. Notable in the result of configuration with E/P=4 is the comparable costs associated with power and energy, the larger contribution of power components in stacks and BOP, and less large contribution of electrolyte and tank which both are

scalable with kWh.

In Noack et al., (2016) 's techno-economic model, the significance of repeating units' costs in a cell stack: membrane, electrode felt, bipolar plate, gasket and frame, is spotted. Unlike most of the prior literature, gasket instead of membrane shares the biggest part within cell stack because of the unique way of manufacture; while frame used for sealing also took a half of the total cost of the membrane.

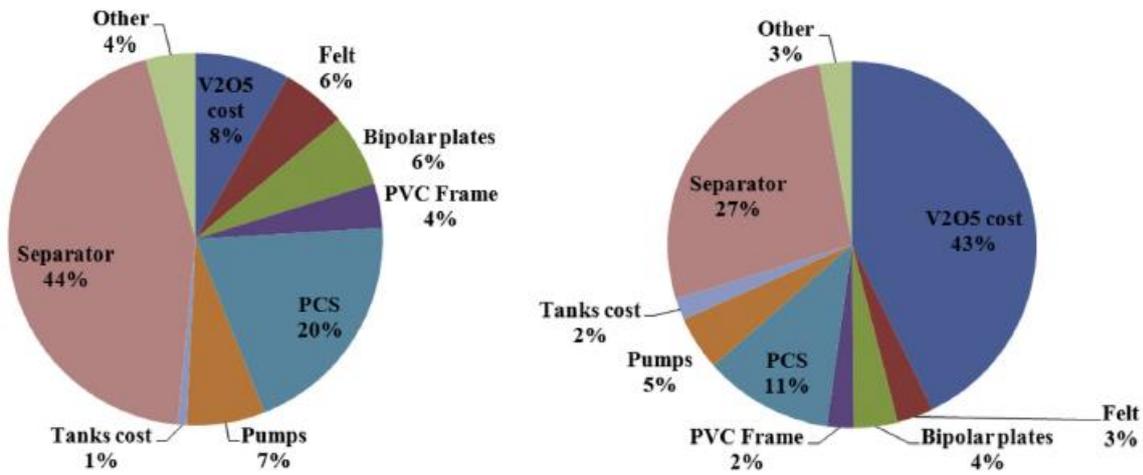


Figure 4 Cost Breakdown for E/P = 0.25 (left) and E/P = 4 (right) (Viswanathan et al., 2014)

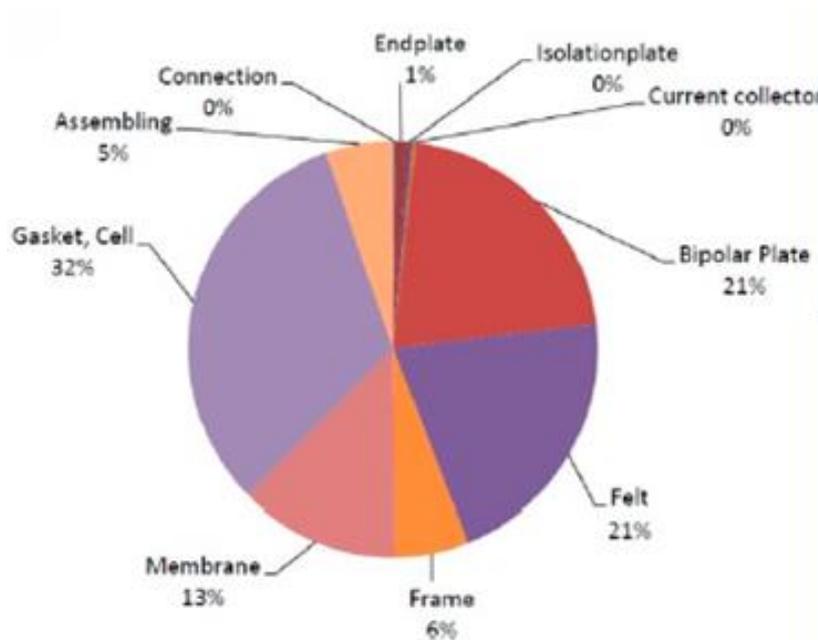


Figure 5 Cell Stack's breakdown (Noack et al., 2016)

## 4.2 Inventory of present and future component's cost

The intriguing results above raised our study interest in deep on these components. This sub-section would intend to focus on costs of Vanadium active species, ion-exchange membrane, electrode felt, bipolar plate, gasket and cell frame. To facilitate subsequent analysis, all cost parameter will be converted to Euro based on historical exchange rates instead of American dollars (“XE: USD / EUR Currency Chart. US Dollar to Euro Rates,” n.d.).

### 4.2.1 Cost of Vanadium active species

As we discussed the last section, vanadium active species could be prepared by either vanadium pentoxide or vanadium oxide sulfate, yet the latter one is “expensive and unfavourable to scale up” than the former one, as such, leading our focus on research in Vanadium Pentoxide (Parasuraman et al., 2013). In table X, most of the in-depth analysis obtained their values for the present scenario from United States Geological Survey (“USGS.gov | Science for a changing world,” n.d.). The cost of vanadium pentoxide specified in prior studies are in a range of 2.66 - 44.3 € per kg and the extremely fluctuated cost brings itself a highly uncertain future. A vanadium expert, Terry Perles from TTP squared, extensively investigated the historical price in vanadium pentoxide (Terry, n.d.). His prediction of 10.07 € per kg strongly based on  $V_2O_5$  price distribution chart from July 2003 to June 2018 with an assumption of the normal market condition. He suggested that the vanadium price, in the long run, is determined by the cost of production. Nowadays, 80% of vanadium production is based on recovery of vanadium from byproducts generated by other industries. The vanadium active species are recovered from slag in China and Russia's steelworks and both ashes and residues resulting from refining or burning oil with high vanadium content. The byproduct nature of supply base means that the supply of raw material is not influenced by vanadium market prices. The high price of vanadium would not incentivise these industries to produce more steel or burn more oil to obtain a

small amount of vanadium, and such unresponsive supply could explain the recent phenomenon of highly varied vanadium price. Mr Perles seemed fairly optimistic about the future landscape of vanadium market; he anticipated a progressive decline to 10.07 € per kg in vanadium cost due to the gradual emergence of new primary vanadium mine to meet the increasing demand. Also, he looked forward to seeing an improved utilization of vanadium electrolyte in the future, increasing the energy storage potential of vanadium in electrolyte from 75% to 90%; which means for each kWh, the system requires less V<sub>2</sub>O<sub>5</sub>, reduced from 10 kg in present scenario to 8.3 kg. Adding the cost of converting V<sub>2</sub>O<sub>5</sub> to electrolyte about 2.3 € per kg, electrolyte's cost of 102 € per kWh is comparable to the result from EPRI report.

| <b>Scenario: Present</b>      |                          |                           |                                |                               |  |
|-------------------------------|--------------------------|---------------------------|--------------------------------|-------------------------------|--|
| <b>Author</b>                 | <b>Source of Data</b>    | <b>Currency specified</b> | <b>Cost \$ kg<sup>-1</sup></b> | <b>Cost € kg<sup>-1</sup></b> | <b>Electrolyte in € kWh<sup>-1</sup></b> |
| EPRI (2007)                   | USGS                     | 2004 \$                   | 3.31                           | <b>2.66</b>                   | -  |
| EPRI (2007)                   | USGS                     | 2005 \$                   | 55.12                          | <b>44.30</b>                  | -  |
| EPRI (2007)                   | USGS                     | 2007 \$                   | 16.22                          | <b>11.85</b>                  | 158.26                                   |
| zhang et al (2011)            | USGS                     | 2011 \$                   | 21.13                          | <b>15.19</b>                  | 101.07                                   |
| Viswanathan et al (2014)      | USGS                     | 2012 \$                   | 24.00                          | <b>18.68</b>                  | 202                                      |
| Darling et al (2014)          | -                        | 2014 \$                   | 29.00                          | <b>21.85</b>                  | 184                                      |
| Crawford et al (2015)         | USGS                     | 2015 \$                   | 24.00                          | <b>21.64</b>                  | 138                                      |
| Zeng et al (2015)             | USGS                     | 2015 \$                   | 14.31                          | <b>12.90</b>                  | 109                                      |
| Moore et al (2015)            | USGS                     | 2015 \$                   | 21.13                          | <b>19.05</b>                  | 53                                       |
| Ha and Gallagher et al (2015) | Darling et al            | 2014 \$                   | 29.00                          | <b>21.85</b>                  | 94                                       |
| Noack et al (2016)            | Some Manufacturer        | 2016 €                    | -                              | <b>5.21</b>                   | 345                                      |
| Milshtein et al (2017)        | ("Chemicals A-Z," n.d.)  | 2017 \$                   | 22.00                          | <b>19.51</b>                  | 41                                       |
| Minke et al (2017)            | IFBF 2012                | 2017 €                    | -                              | <b>20.00</b>                  | 283                                      |
| Terry Perles (2018)           | President of TTP Squared | 2018 \$                   | 38.21                          | <b>31.70</b>                  | 316                                      |

| <b>Scenario: Future</b>  |                       |                           |                                |                               |  |
|--------------------------|-----------------------|---------------------------|--------------------------------|-------------------------------|--|
| <b>Author</b>            | <b>Source of Data</b> | <b>Currency specified</b> | <b>Cost \$ kg<sup>-1</sup></b> | <b>Cost € kg<sup>-1</sup></b> | <b>Electrolyte in € kWh<sup>-1</sup></b> |
| EPRI (2007)              | USGS                  | 2007 \$                   | 9.92                           | <b>7.25</b>                   | 102                                      |
| Viswanathan et al (2014) | USGS                  | 2012 \$                   | 8.00                           | <b>6.23</b>                   | 82                                       |

|                               |                          |         |       |              |     |
|-------------------------------|--------------------------|---------|-------|--------------|-----|
| Darling et al (2014)          | -                        | 2014 \$ | 20    | <b>15.07</b> | -   |
| Crawford et al (2015)         | USGS                     | 2015 \$ | 8.00  | <b>7.21</b>  | -   |
| Ha and Gallagher et al (2015) | Darling et al            | 2014 \$ | 22.00 | <b>16.58</b> | -   |
| Milshtein et al (2017)        | ("Chemicals A-Z," n.d.)  | 2017 \$ | 5.00  | <b>4.43</b>  | -   |
| Terry Perles (2018)           | President of TTP Squared | 2018 \$ | 12.13 | <b>10.07</b> | 102 |

Table 5 Present and future cost of vanadium pentoxide

#### 4.2.2 Cost of Ion-exchange Membrane

Ion-exchange membrane requires high manufacture standard due to its unique function on flow battery. In table X, a detailed cost summary of the ion-exchange membrane is made. Most of the studies took Viswanathan et al.'s Nafion membrane cost input from various vendors as a reference, thus, their cost values slightly vary from 350 to 450 € per m<sup>2</sup> because of the fluctuation of USD/EUR exchange rate. However, one of the attendees of IFBF 2018, The Chemours Company listed its Nafion membrane price as 1384 € per m<sup>2</sup> in Nafion™ web store, which brought such a huge difference between quotation and listed price. Beside Nafion, Milshtein et al (2017) suggested a low-cost porous separator typically used in the lithium-ion battery to the flow system. The porous separator could avoid large active species to pass freely across the opposite side while maintaining the overall chemical charge balance. Although the major drawbacks of the porous separator are leading to slower transport rate and higher cost of active species, its cost could go as low as 27 € per m<sup>2</sup>, approximately 1/16 of the Nafion price within the same study. About future scenario, apart from Viswanathan et al.'s study, prior studies used values cited from James et al (2014) who investigate on mass production cost estimation for fuel cell systems. Since fuel cell, as a more mature technology, has a similar cell structure as flow battery does, the fact that it also requires Nafion proton exchange membrane in each cell helps such comparison have a certain reference value.

#### Scenario Present

| Author      | Source of Data  | Currency Specified | Item Specification    | Cost \$ m <sup>-2</sup> | Cost € m <sup>-2</sup> | Cost € kW <sup>-1</sup> |
|-------------|-----------------|--------------------|-----------------------|-------------------------|------------------------|-------------------------|
| EPRI (2007) | Dupont Chemical | 2007 \$            | Dupont Nafion 1/2 mil | 237.5                   | <b>173.56</b>          | 389                     |

|                               |                                   |         |                   |         |                |     |
|-------------------------------|-----------------------------------|---------|-------------------|---------|----------------|-----|
| Zhang et al (2012)            | EPRI                              | 2011 \$ | -                 | 500     | <b>359.42</b>  | -   |
| Viswanathan et al (2014)      | "various vendors"                 | 2012 \$ | Nafion 117        | 500     | <b>389.15</b>  | 266 |
| Darling et al (2014)          | Viswanathan et al                 | 2014 \$ | Nafion 50 $\mu$ m | 500     | <b>376.80</b>  | -   |
| Crawford et al (2015)         | 45% cost of Viswanathan et al     | 2015 \$ | Nafion 212        | 225     | <b>202.88</b>  | -   |
| Zeng et al (2015)             | Viswanathan et al                 | 2015 \$ | Nafion 212        | 500     | <b>450.85</b>  | 313 |
| Ha and Gallagher et al (2015) | Viswanathan et al                 | 2014 \$ | Nafion            | 500     | <b>376.80</b>  | -   |
| Noack et al (2016)            | "Various Manufacturer"            | 2016 €  | -                 | -       | <b>250.00</b>  | 665 |
| Milshtein et al (2017)        | Viswanathan et al , Darling et al | 2017 \$ | Nafion            | 500     | <b>452.09</b>  | -   |
| Milshtein et al (2017)        | (Zhu et al., 2009)                | 2017 \$ | Porous Seperator  | 30      | <b>27.13</b>   | -   |
| Minke et al (2017)            | Minke et al (2015)                | 2017 €  | Nafion 117 7mil   | -       | <b>400.00</b>  | 324 |
| Minke et al (2017)            | Minke et al (2015)                | 2017 €  | SPEEK             | -       | <b>60.00</b>   | 48  |
| Chemours                      | Nafion(TM) Store                  | 2018 \$ | Nafion 117 8mil   | 1668.85 | <b>1384.66</b> | -   |

#### Scenario Future

| Author                        | Source of Data                    | Currency Specified | Item Specification    | Cost \$ m <sup>-2</sup> | Cost € m <sup>-2</sup> | Cost € kW <sup>-1</sup> |
|-------------------------------|-----------------------------------|--------------------|-----------------------|-------------------------|------------------------|-------------------------|
| EPRI(2007)                    | Dupont Chemical                   | 2007 \$            | Dupont Nafion 1/2 mil | 45                      | <b>32.89</b>           | 77                      |
| Viswanathan et al (2014)      | "various vendors"                 | 2012 \$            | Nafion 117            | 200                     | <b>155.66</b>          | 108                     |
| Darling et al (2014)          | (James et al., n.d.)+ EPRI        | 2014 \$            | Nafion 50 $\mu$ m     | 50                      | <b>37.68</b>           | -                       |
| Crawford et al (2015)         | 45% cost of Viswanathan et al     | 2015 \$            | Nafion 212            | 90                      | <b>81.15</b>           | -                       |
| Ha and Gallagher et al (2015) | (James et al., n.d.)              | 2014 \$            | Nafion                | 50                      | <b>37.68</b>           | -                       |
| Milshtein et al (2017)        | Viswanathan et al , Darling et al | 2017 \$            | Nafion                | 50                      | <b>45.21</b>           | -                       |
| Milshtein et al (2017)        | Darling et al                     | 2017 \$            | Porous Separator      | 1                       | <b>0.90</b>            | -                       |

Table 6 Present and future cost of Ion-Exchange Membrane

### 4.2.3 Cost of Bipolar Plate and Electrode Felt

Table X shows a general summary of the cost of the bipolar plate and electrode felt. Early published studies from 2007 to 2015 identified a relatively low price in both items in present scenario – for bipolar plates ,5.28-58.46 € per m<sup>2</sup>; while for electrode felt, 14.38-63.12 € per m<sup>2</sup>, yet recent sources indicated high values in components, 200-418 € per m<sup>2</sup> for bipolar plate and 60-160 € per m<sup>2</sup> for electrode felt. For future scenario, literature based on studies from Viswanathan et al and James et al, indicated price ranges (5.28-32.89 € per m<sup>2</sup> for BBP; 12.79-18.03 € per m<sup>2</sup> for electrode felt). One of the BBP and felt supplier which attended IFBF 2018, SGL was uncertain whether an increase of RFB stack

size could slash components' price to as low as the values Viswanathan et al. specified; but acknowledged studies from Minke et al. and SGL Carbon, which current components' price could reduce up to 40% and 50 % for BPP and electrode felt respectively. They mentioned the slow growth in demand from VFB developers and persistent increase of material precursor's cost are the two biggest resistances to the price drop.

| <b>Scenario Present</b>       |   |                           |                             |                        |                          |                                       |                              |                        |                          |
|-------------------------------|---|---------------------------|-----------------------------|------------------------|--------------------------|---------------------------------------|------------------------------|------------------------|--------------------------|
| <b>Author</b>                 | <b>Source of Data</b>                     | <b>Currency Specified</b> | <b>Bipolar Plate's Cost</b> |                        |                          | <b>Electrode's Item Specification</b> | <b>Electrode Felt's Cost</b> |                        |                          |
|                               |   |                           | <b>\$m<sup>-2</sup></b>     | <b>€m<sup>-2</sup></b> | <b>€ kW<sup>-1</sup></b> |                                       | <b>\$m<sup>-2</sup></b>      | <b>€m<sup>-2</sup></b> | <b>€ kW<sup>-1</sup></b> |
| EPRI (2007)                   | "developers and standard product catalog" | 2007 \$                   | 80                          | <b>58.46</b>           | 180                      | PAN-based                             | 50                           | <b>36.54</b>           | 180                      |
| Zhang et al (2012)            | EPRI                                      | 2011 \$                   | 51                          | <b>36.66</b>           | -                        | -                                     | 20                           | <b>14.38</b>           | -                        |
| Viswanathan et al (2014)      | "Various Vendors"                         | 2012 \$                   | 55                          | <b>42.81</b>           | 37                       | -                                     | 70                           | <b>54.48</b>           | 33                       |
| Darling et al (2014)          | Viswanathan et al                         | 2014 \$                   | 55                          | <b>41.45</b>           | -                        | -                                     | 70                           | <b>52.75</b>           | -                        |
| Crawford et al (2015)         | Viswanathan et al                         | 2015 \$                   | 55                          | <b>49.59</b>           | -                        | -                                     | 70                           | <b>63.12</b>           | -                        |
| Zeng et al (2015)             | Viswanathan et al                         | 2015 \$                   | 55                          | <b>49.59</b>           | 33                       | SGL,GFA 6                             | 70                           | <b>63.12</b>           | 82                       |
| Ha and Gallagher et al (2015) | (Southworth, n.d.)                        | 2014 \$                   | 7                           | <b>5.28</b>            | -                        | -                                     | 70                           | <b>52.75</b>           | -                        |
| Noack et al (2016)            | "Various Manufactuer"                     | 2016 €                    | -                           | <b>418.00</b>          | 1121                     | -                                     | -                            | <b>150.00</b>          | 1104                     |
| Minke et al (2017)            | Minke et al (2015)                        | 2017 €                    | -                           | <b>200.00</b>          | 168                      | Carbon Felt                           | -                            | <b>60.00</b>           | 96                       |
| SGL (2018)                    | SGL and Minke et al (2015-2017)           | 2018 €                    | -                           | <b>240.00</b>          | -                        | PAN-based & Rayon                     | -                            | <b>135.00</b>          | -                        |

| <b>Scenario Future</b>        |   |                           |                             |                        |                          |                           |                              |                        |                          |
|-------------------------------|---|---------------------------|-----------------------------|------------------------|--------------------------|---------------------------|------------------------------|------------------------|--------------------------|
| <b>Author</b>                 | <b>Source of Data</b>                     | <b>Currency Specified</b> | <b>Bipolar Plate's Cost</b> |                        |                          | <b>Item Specification</b> | <b>Electrode Felt's Cost</b> |                        |                          |
|                               |   |                           | <b>\$m<sup>-2</sup></b>     | <b>€m<sup>-2</sup></b> | <b>€ kW<sup>-1</sup></b> |                           | <b>\$m<sup>-2</sup></b>      | <b>€m<sup>-2</sup></b> | <b>€ kW<sup>-1</sup></b> |
| EPRI (2007)                   | "developers and standard product catalog" | 2007 \$                   | 45                          | <b>32.89</b>           | 56                       | Pan-Based                 | 17.5                         | <b>12.79</b>           | 56                       |
| Viswanathan et al (2014)      | "Various Vendors"                         | 2012 \$                   | 25                          | <b>19.46</b>           | 14.5                     | -                         | 20                           | <b>15.57</b>           | 13                       |
| Darling et al (2014)          | (James et al., n.d.)                      | 2014 \$                   | 30                          | <b>22.61</b>           | -                        | -                         | 20.00                        | <b>15.07</b>           | -                        |
| Crawford et al (2015)         | Viswanathan et al                         | 2015 \$                   | 25                          | <b>22.54</b>           | -                        | -                         | 20                           | <b>18.03</b>           | -                        |
| Ha and Gallagher et al (2015) | (James et al., n.d.)                      | 2014 \$                   | 7                           | <b>5.28</b>            | -                        | -                         | 20                           | <b>15.07</b>           | -                        |
| SGL (2018)                    | Minke et al                               | 2018 €                    | -                           | <b>150.00</b>          | -                        | -                         | -                            | <b>67.5</b>            | -                        |

Table 7 Present and future cost of bipolar plate and electrode felt

#### 4.2.4 Cost of Cell Frames and gasket

Little publicly available information about the cost of cell frame and gasket within the VRFB system. Values for cell frame used to conduct cost models for present scenarios in studies ranged from 2.26 to 100 € per m<sup>2</sup>; while for the gasket, from 2.26 to 392 € per m<sup>2</sup>. The extreme value of 392 € per m<sup>2</sup> was from Noack et al.'s studies, it specified that the cured-in-place gasket with a unique way of manufacturing comprised the largest share of the cell stack's cost. Since most of their values are less significant to other components, prior literature rarely compiled their cost in € per kW but in Noack et al (2016) about 1697.4 € per kW. However, in James et al (2018) about the study of mass production cost estimation for fuel cell systems, it assessed the cost of manufacturing fuel cell systems with various production rate. The coolant gasket which is sandwiched between flow plates in the fuel cell has a similar function of the gasket in flow battery in preventing leakage. In their 2017 publication, the cost of coolant gasket decreased from 4.63 € per kW to 0.45 € per kW (1.07 € per m<sup>2</sup> to 0.103 € per m<sup>2</sup> if converting in Noack et al.'s model) when the annual production rate with laser welding increased from 1000 to 500,000. The cost of cell frame (stack housing in James et al.' study) from insertion moulding followed by vacuum thermo-forming, dropped from 0.7 € per kWh to 0.062 € per kWh (0.258 € per m<sup>2</sup> to 0.022 € per m<sup>2</sup> converted from Noack et al.'s model). Although both the cost of components currently are initially high, there is still a big room for cost reduction when VRFB is in a high deployment rate.

Scenario: Present

| Author                        | Source of Data         | Currency Specified | Cell Frame's Cost  |                   | Gasket's Cost      |                   |
|-------------------------------|------------------------|--------------------|--------------------|-------------------|--------------------|-------------------|
|                               |                        |                    | \$ m <sup>-2</sup> | € m <sup>-2</sup> | \$ m <sup>-2</sup> | € m <sup>-2</sup> |
| Viswanathan et al (2014)      | "Various Vendors"      | 2012 \$            | 16.56              | <b>12.89</b>      | 25.51              | <b>19.85</b>      |
| Darling et al (2014)          | -                      | 2014 \$            | 3.00               | <b>2.26</b>       | 3.00               | <b>2.26</b>       |
| Crawford et al (2015)         | Viswanathan et al      | 2015 \$            | 16.56              | <b>14.93</b>      | 25.51              | <b>23.00</b>      |
| Ha and Gallagher et al (2015) | Darling et al.         | 2014 \$            | 3.00               | <b>2.26</b>       | 3.00               | <b>2.26</b>       |
| Noack et al (2016)            | "Various Manufacturer" | 2016 €             | -                  | <b>100.00</b>     | -                  | <b>392.00</b>     |

|                    |   |        |   |               |   |               |
|--------------------|---|--------|---|---------------|---|---------------|
| Minke et al (2017) | - | 2017 € | - | <b>100.00</b> | - | <b>100.00</b> |
|--------------------|---|--------|---|---------------|---|---------------|

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Scenario Future

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| Author                        | Source of Data    | Currency | Cell Frame's Cost |                    | Gasket's Cost     |                    |
|-------------------------------|-------------------|----------|-------------------|--------------------|-------------------|--------------------|
|                               |                   |          | Specified         | \$ m <sup>-2</sup> | € m <sup>-2</sup> | \$ m <sup>-2</sup> |
| Viswanathan et al (2014)      | "Various Vendors" | 2012 \$  | 3.2               | <b>2.49</b>        | 10.20             | <b>7.94</b>        |
| Darling et al (2014)          | -                 | 2014 \$  | 1                 | <b>0.75</b>        | 1.00              | <b>0.75</b>        |
| Crawford et al (2015)         | Viswanathan et al | 2015 \$  | 3.2               | <b>2.89</b>        | 10.20             | <b>9.20</b>        |
| Ha and Gallagher et al (2015) | Darling et al.    | 2014 \$  | 1                 | <b>0.75</b>        | 1                 | <b>0.75</b>        |

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Table 8 Present and future cost of cell frame and gasket

### 4.3 Review on prior research on cost trend of VRFB

The table below summarize the system capital cost, expressed in € per kWh, from various reports and studies. In Viswanathan et al.'s model, two configurations with different Energy to power ratio/duration are examined, the system capital cost in 15-minute system was about 9 times higher than that in the 4-hour system due to the strong influence of expensive power components with little cheaper energy component. These findings manifested systems shifting to a long-hour application could be beneficial to a lower system capital cost. Except the extreme case in Viswanathan et al, the capital cost at the present scenario ranged from 277 to 1078 € per kWh. The highest value 1078 € per kWh was from Noack et al.'s study. Noack et al.'s model has a relatively high cost input in power components although its model's duration appeared the highest in 12 hours. As they assumed a low deployment rate of vanadium flow battery, they introduced fabrication cost and material factor on top of the original expensive material cost to demonstrate the reality in experimental lab or pilot plant, the model will be further explained in great detail in a later section. Both studies from Darling et al. and Ha and Gallagher et al. provided an estimate of system costs for VRB with the assumption of annual demand of 10 GWh of energy storage as the high volume future state. Lazard's Levelized cost of storage evaluated the cost of vanadium flow batteries in various applications such as Peaker Replacement(100 MW), distribution substation(10 MW) and microgrid (1MW), and since energy and power rating of VRFBs are highly decoupled, cost per capacity varies remarkably between

applications. For future scenario, the estimated capital cost is in the wide range of 79 to 1254.75 € per kWh, reflecting a huge uncertainty about the future cost of VRFB.

| <b>Report</b>                             | <b>Currency Specified</b> | <b>Power Rating kW</b> | <b>Duration hr</b> | <b>Current Capital Cost €/kWh</b> | <b>Future Capital Cost €/kWh</b> |
|---|---------------------------|------------------------|--------------------|-----------------------------------|----------------------------------|
| Viswanathan et al.(2014)                  | 2014 \$                   | 1000                   | 0.25               | <b>3094.29</b>                    | <b>1254.75</b>                   |
| Viswanathan et al.(2014)                  | 2014 \$                   | 1000                   | 4                  | <b>336.86</b>                     | <b>136.40</b>                    |
| Lazard's Levelized Cost of Storage (2017) | 2017 \$                   | 100000                 | 4                  | <b>277.91</b>                     | -                                |
| Lazard's Levelized Cost of Storage (2017) | 2017 \$                   | 1000                   | 4                  | <b>632.91</b>                     | -                                |
| Minke et al (2017)                        | 2017 €                    | 10000                  | 4                  | <b>655.00</b>                     | <b>285</b>                       |
| Moore et al. (2015)                       | 2015 \$                   | 1000                   | 6                  | <b>328.62</b>                     | -                                |
| Lazard's Levelized Cost of Storage (2017) | 2017 \$                   | 10000                  | 6                  | <b>366.67</b>                     | -                                |
| EPRI                                      | 2007 \$                   | 1000                   | 8                  | <b>452.17</b>                     | <b>401.25</b>                    |
| Minke et al (2017)                        | 2017 €                    | 10000                  | 8                  | <b>520.00</b>                     | <b>186</b>                       |
| Noack et al (2016)                        | 2016 €                    | 10                     | 12                 | <b>1078.00</b>                    | -                                |
| Darling et al (2014)                      | 2014 \$                   | -                      | -                  | <b>422.02</b>                     | <b>88</b>                        |
| Ha and Gallagher et al (2015)             | 2015 \$                   | -                      | -                  | <b>279.53</b>                     | <b>142.47</b>                    |
| IRENA (2017)                              | 2016 \$                   | -                      | -                  | <b>290.14</b>                     | <b>191.49</b>                    |
| Milshtein et al.(2017)                    | 2017 \$                   | -                      | -                  | <b>377.81</b>                     | <b>79.35</b>                     |

Table 9 Present and future cost of vanadium flow battery systems

#### 4.4 Motivation and drivers of VRFB cost reduction over time

Innovation strategy to drive down VRFB's cost involves two basic mechanisms: technology-push (technology breakthrough by research) and demand-pull (creating demand of a technology to trigger product's development) ("Which innovation strategy," n.d.). Whether the strategy is push or pull, it consists of a support's locus: endogenous(private market) or exogenous(Exclude private market, in respect of low-carbon technology, normally referring government and social aspect).(AFLAKI et al., n.d.) In the following part, various prevailing cost-cutting instruments and strategies would be introduced.

**Public R&D investment** appears as an exogenic technology-push strategy. Government funding is a crucial and positive driver to innovation creation and diffusion with subsidizing research institutes. In terms of vanadium flow battery, Australia, Japan, China and Korea vaulted to the leading position in the global market of VRFB because of their persistent R&D effort. Australian Renewable Energy Agency (ARENA) had issues more than US\$ 197 million to support energy storage technology including flow battery in Australia. In Japan, “New Sunshine Project” involved solar power generation and storage technology, invested not less than US\$11 billion for their fundamental scientific research and commercialization of solar power. History has told this R&D investment had helped achieved substantial decrease in clean energy price, for instance, cost of solar panel in Japan dropped from \$350/W to \$5.4/W within 1974-2005 due to the effort of public R&D investment(AFLAKI et al., n.d.). In Korea, Korea’s Ministry of Trade, Industry and Energy (MOTIE) released the “2<sup>nd</sup> Energy Master Plan” and intended to reduce all energy storage system cost by half(“Research on Energy Storage Technologies to Build Sustainable Energy Systems in the APEC Region,” n.d.). The single most striking observation of the R&D of VRFB from previous studies was its improvement in cell’s voltage efficiency. With academic groups and industries restlessly investigating how materials and operation modes vary VRFB’s output performance, progressive increase in voltage and energy efficiency was achieved (Parasuraman et al., 2013), and we expect that these recent public funding would even bring more opportunity in such aspect in the future.

**Demand-oriented/renewable energy support policies** create an encouraging atmosphere to help specific technology be adopted or diffused to a society. In terms of renewable energy technology, the governments endogenously introduce instruments such as feed-in tariff, quotas and price driven policy like carbon taxes to urge both innovation creation and diffusion.(Nemet and Baker, 2009) Since VRFB possesses compatible applications with intermittent renewable energy sources, the deployment of new renewable systems implies that demand of RFB would also be increased and help reduce VRFB’s costs. The demand-pull mechanism often complements push strategy in avoidance

of lock-in of dominant technologies(AFLAKI et al., n.d.). The Korean national utility, the Korea Electric Power Corporation (KEPCO) offered the energy storage users discount rates in electricity and demand charges and rewarded those system which can provide capacity during peak-hour with a better discount rate. The flexible electricity rate design encouraged installing flexible battery systems such as vanadium flow battery to support the grid during peak-hour(“Research on Energy Storage Technologies to Build Sustainable Energy Systems in the APEC Region,” n.d.). With such incentives to deploy VRFBs, we would anticipate that VRFB system’s capital cost could be greatly reduced by economies of scale and learning effects in order to meet the increasing demands.

**Economies of scale** describes a phenomenon of decline in production per-unit cost when total demand increases. (Junginger et al., 2010; “Presenting the Future,” n.d.) As more bulk orders anticipated from manufacturers, there will be following upgrades of production chain line, labors are trained to be more specialized in specific roles, machines trend to be more integrated and automated in order to boost production volume. Because of the innate scalability with power-energy decoupling features in RFB (Choi et al., 2016; Doughty et al., 2010; Gong et al., 2015; L. Li et al., 2011; Moore et al., 2015; Weber et al., 2011; Xu et al., 2011; Zhao et al., 2015), it could significantly benefit from economies of scale in cost reduction(“Despite technological advances, flow batteries struggle against market giant lithium-ion,” n.d.). The phenomenon is coherent to the view of most of the material suppliers of VRFB such as SGL and The Chemours. Especially for these highly repeating units of electrode felt and membranes within a cell stack, the larger the order is, the more potential for reduction in cost per unit. Also, it is reasonable to expected that the cost of auxiliary systems such as control system and fluid regulation systems will have a tendency of decrease as well in the future.

**Endogenous Learning effect** can be divided into four categories to reduce product’s capital cost: (Junginger et al., 2010; “Presenting the Future,” n.d.)

*Learning-by-researching* reflects R&D effort on fundamental concepts in particular system. In respect of flow batteries, compared to a much more commercialized electrochemical storage- Li-ion battery, flow battery remains at an early stage in the market, and most of the technological achievement to date have been in laboratory instead of factories. For instances, Liyu Li's effort on widening operating temperature window of true-vanadium flow battery, superseding expensive vanadium electrolyte with cheap and easily accessible metal, zinc-iron couples by Gong, and organic redox couples developed in Harvard University. ("Despite technological advances, flow batteries struggle against market giant lithium-ion," n.d.; Gong et al., 2015; L. Li et al., 2011) It is expected that R&D would take a huge part to bring down VRFB's cost.

*Learning-by-doing* illustrates how productivity increase with cumulative experience. This idea was firstly presented by Theodore Wright. Certain reference value could be found at the study in mass production of fuel cell system from James et al. (2018) due to the similar cell structure to VRFB. For bipolar plate, fuel cell manufacturer could introduce fully automated stamping press system with robots to increase productivity; for gasket, a 3M patented manufacturing process train could utilize robotic pick-and-place machinery to facilitate the whole process by quickly placing the materials on working platform.

*Learning-by-using* refers technology's supplier digest customer's feedback to improve product's performance. Since early 1990s, flow battery developers have started to build customer relationships with several companies, especially in Japan and Australia, they help install VRFBs, evaluate their performance for various applications and keep upgrading the energy and power capacity (Leung et al., 2012), thus development of VRFB involves plenty of learning-by-using to cut cost.

*Learning-by-interacting* highlights the interaction and synergy between actors such as R&D industries, manufacturers and policy makers. Back in 1986, Research institute ,Unisearch embodied a highly

cooperative spirit on developing flow battery with dispersing patent license of vanadium-based flow battery to different organization, continuing further investigations, and which synergy has facilitated the development progress of VRFB(Leung et al., 2012).

|                   | <b>Technology-Push</b>  | <b>Demand-Pull</b>   |
|-------------------|---|--|
| <b>Exogenous</b>  | <ul style="list-style-type: none"> <li>• Public R&amp;D Investment</li> </ul>                     | <ul style="list-style-type: none"> <li>• Demand-Oriented Policy such as FIT, TGC</li> </ul>      |
| <b>Endogenous</b> | <ul style="list-style-type: none"> <li>• Economies of Scale</li> <li>• Learning Effect</li> </ul> | <ul style="list-style-type: none"> <li>• Economic Growth (outside the scope of study)</li> </ul> |

Table 10 Drivers to cost reduction of clean technologies

## 5. Methodology to project future technology costs

### 5.1 Introduction

A number of techniques have been developed to project the future cost of VRFB, they are learning curve analysis, expert elicitation and bottom-up modelling.

#### 5.1.1 Learning Curve Analysis

It is an approach to predict the future cost based on historical trends and events. A learning parameter constructed by different drivers on reducing the cost of, in this case, redox flow battery, is assumed to govern the future price movement of RFB. Three factors would impact learning process: task complexity, structure of training programs, worker's motivation in performing tasks and prior experience with the task(Jaber, 2014). A recent study from The Grantham Institute for Climate Change in Imperial College London by Schmidt et al. predicted the future system cost of vanadium flow battery based on experience rates and distinctly plotted its cost result against years, cumulative installed nominal capacity and cumulative investment(Schmidt et al., 2017). However, due to the relatively low level of commercialization of the technology to date, the study lacked the historical cost information of vanadium flow battery; only four data sources from US department of Energy and some leading manufacturers in Energy Storage Europe 2016 Conference were used in the learning curve analysis; the small size of the dataset meant that which future cost could be highly uncertain. Also, because of the limitation of learning curve analysis, the study could not identify technological specific improvement which could be done to reduce system's cost but a macroscopic view of cost forecast under certain circumstances.

### 5.1.2 Expert Elicitation

Expert elicitation is a methodology to acquire probabilistic belief statements from expert to quantify uncertainties.(Colson and Cooke, 2018) This method could enquire into the cost of VRFB in an organized, structured interview with educated experts or experienced manufacturers in order to elicit a scope of probable RFB's cost at a particular date with high-level judgement. The integrity and reliability of the approach highly depends on the expert's belief and their ways to quantify uncertainty. It is possible that the expert's prediction on RFB's cost are based on the other two methodologies. Due to the lack of previous related investigations, the existing data and modeling tool fails to provide sufficient information about cost reduction on RFB, thus expert elicitation presents as an advantage to provide quantified subjective beliefs for RFB's future cost projection(Colson and Cooke, 2018; Usher and Strachan, 2013). The Grantham Institute for Climate Change is continuing their investigation on the potential role of different electricity storage technologies in future low-carbon electricity systems through expert elicitation, they had been seeking the views of experts in Lithium-ion battery and electrolysis, soon or later, there will be one for vanadium flow battery.

### 5.1.3 Bottom-up modelling

A bottom-up modelling approach disintegrates an investigated system into components. To date, there are sufficient existing VRFB component-based cost data to justify a bottom-up modelling approach. These information can be obtained through literature or interview with manufacturer ("Presenting the Future," 2016). Each of the components will be individually investigated to observe how technical advances, material price's trend and economies of scales bring down the system's capital cost. A major advantage of bottom-up analysis is that it could highlight certain components or functional changes presenting sensitively in price within the system. Also, it could combine with parametric modeling to show the cost in different battery system setups such as varying operating parameters

like current density and SOC (Mukora et al., 2009). Bottom-up modeling appeared really useful in an early stage to identify what radical change could be done to cut down the system's cost. However, it is inadequate to determine how the cost trend varies through the years if only little information as cost input is acquired to compute the model. Viswanathan et al. (2014) and Darling et al. (2014) did not specify a particular year for the future state, instead, making cost-input assumptions for near-term and optimistic cases.

|                            | <b>Approach</b>   | <b>Strength</b>   | <b>Weakness</b>   |
|----------------------------|---|---|---|
| <i>Learning Curves</i>     | <ul style="list-style-type: none"> <li>Mathematical function in cost reduction with cumulative experience</li> <li>Model cost based on system's real cost, aggregated in nature.</li> </ul> | <ul style="list-style-type: none"> <li>Long-term prediction</li> <li>Global assessment with historical studies backing</li> <li>Indication of technology's deployment level and the corresponding investment required to "buy down" the cost curve</li> <li>Assist in allocation of resource into different technologies</li> </ul>   | <ul style="list-style-type: none"> <li>Outcome orientated rather than process focused</li> <li>Lack of details about technology-specific casual factors that help reduce system's cost</li> <li>Difficult to predict with variable learning rates throughout the period examined</li> <li>Inability to forecast whether and when market diffusion will happen</li> <li>Inaccuracy of learning curve model with emerging technologies due to insufficient available information</li> <li>Error might take place with currency conversion, inflation and unclear definition of system boundaries</li> </ul> |
| <i>Bottom-up modelling</i> | <ul style="list-style-type: none"> <li>Cost estimation in bottom-up approach, disaggregate a system into individual components with detailed practical analysis</li> </ul>                  | <ul style="list-style-type: none"> <li>Comprehensive understanding of technology-specific casual factors which could potentially cut down the cost</li> <li>Detailed scope of practical improvements within a system is raised</li> <li>Need not necessarily rely on historical trends</li> <li>Provide insight for radical change instead of incremental change like the case in learning curve</li> </ul> | <ul style="list-style-type: none"> <li>Difficult to obtain cost details from technologies in early stage because of limited information available</li> <li>Inability to predict long-term system's cost trends to facilitate policy making without integrating other complementary methodologies such as learning curves</li> </ul>   |
| <i>Expert Elicitation</i>  | <ul style="list-style-type: none"> <li>An approach whereby an interview with expert is utilized to quantify</li> </ul>  | <ul style="list-style-type: none"> <li>Capable of providing quantified subjective belief for parameters without the need of historic data resources, in favor of new technologies</li> </ul>  | <ul style="list-style-type: none"> <li>Detrimental effects of bias and heuristics</li> <li>Opinions might contradict towards each other, parameters have to be described in probability distribution</li> </ul>   |

|                      |  |
|----------------------|--|
| uncertainty and make | • Sound scientific judgements are made |
| probabilistic        | from educated experts in diversified   |
| judgement            | related backgrounds and experienced    |
|                      | manufacturer                           |

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Table 11 Strengths and Weaknesses of methodologies (Colson and Cooke, 2018; Mukora et al., 2009; “Presenting the Future,” n.d.; Usher and Strachan, 2013)

## 5.2 Model’s description

The paper reviewed previous literature to identify components that a vanadium flow battery consists of. Bottom-up approach was previously used in EPRI. (2007), Viswanathan et al. (2014), Darling et al. (2014), Noack et al. (2016) and Minke et al. (2017) to estimate VRFB’s capital cost with their original models. Most of the previous cost studies agreed with cell stacks as power component which cost scales with power rating in kW and vanadium electrolyte energy component which cost scales with capacity in kWh. However, depending on the system boundary, definition of “Balance of Plant” (BOP) and its cost unit varies between studies. The early study, BOP in EPRI (2007), which expressed in a fixed cost, was referring the land and construction cost, the building and site preparation cost and the control system cost; while in a later study from Darling et al. (2014), the more inclusive expression of BOP represented some power-scaled components such as temperature regulating equipment, state-of-charge control system, power conversion system and fluid regulating systems. However , BOP was not specified in other studies which had broken down the system into even smaller fragments(Noack et al., 2016; Viswanathan et al., 2014). In this study, to highlight the major six components within cell stacks and electrolyte, BOP will be defined as components other than cell stacks and electrolyte.

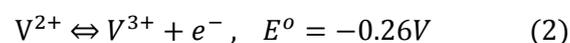
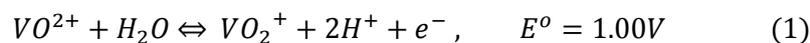
To determine whether vanadium flow battery would be reduced in cost and able to compete lithium-ion battery in the future, this paper uses the bottom-up modelling framework from Noack et al (2016).

Noack et al. (2016) mainly focused on the variation of system cost in different operating parameters like voltage and current density and material's properties such as conductivity; whereas this paper will shift focus to the cost implication of future component price and system capital cost because these operating parameters are less influential to reduce the VRFB's system capital cost for a rapid deployment in the future. (Noack et al., 2016).

### 5.2.1 Electrochemistry of All Vanadium Flow Battery

The cost of the power stack in vanadium battery system has a great dependency on the electric potential generated by each cell. The less the electric potential each cell provides, the more number of cell is required to achieve certain power rating, therefore, more cell components such as ion exchange membrane and electrode felt, are needed in a system, resulted in a high cost of cell stacks. It is crucial to understand what the fundamental electrochemistry is behind to govern VRFB's voltage.

The all vanadium flow battery system utilizes the property of multi oxidation state of vanadium metal, employing V(II) V(III) V(IV) and V(V) redox couples to generate power.



Electric potential  $\varepsilon_{rev}$  of the vanadium full-cell reaction will be around 1.26 V.

The theoretical electric potential  $\varepsilon_{rev}$  drops due to several causes: activation losses, ohmic losses and mass transport loss.

$$\varepsilon_{cell} = \varepsilon_{rev} - \varepsilon_{act} - \varepsilon_{ohm} - \varepsilon_{mass} \quad (3)$$

Activation loss takes place because of the slow reactions at electrodes, it significantly depends on electrode material, reaction temperature, presence of catalyst and flow rate of reactant. The loss can be explained by Butler-Volmer equation in details; while mass transport loss happens as the fast reactant depleted rate creates inactive voids to the electrode, therefore the pump system should sufficiently supply reactant to the cell stack in avoidance of mass transport loss.

$$\varepsilon_{act} = \alpha * \ln\left(\frac{i}{i_o}\right) \quad (4)$$

$$\varepsilon_{mass} = \frac{RT}{nF} * \ln\left(\frac{i_l}{i_l - i}\right) \quad (5)$$

Regarding previous literature,  $\alpha$ ,  $i_l$  and  $i_o$  is hard to be experimentally determined, thus activation loss and mass transport loss will be left as constants. Nonetheless, calculation on ohmic loss in the reaction is achievable. Ohmic loss is strongly material dependent, this can be evaluated with different resistances of the components such as bipolar plates, carbon felt, ion exchange membrane, electrolyte and also resistance from contact.

$$\varepsilon_{ohm} = i * (R_{membrane} + 2R_{carbon\ felt} + R_{BPP} + R_{electolyte} + R_{contact}) \quad (6)$$

$$\varepsilon_{ohm} = i * \left( \frac{t_{membrane}}{A_{membrane} \sigma_{membrane}} + 2 \frac{t_{felt}}{A_{felt} \sigma_{felt}} + \frac{t_{BPP}}{A_{BPP} \sigma_{BPP}} + R_{electolyte} + R_{contact} \right) \quad (7)$$

Where  $t$  (cm) is thickness,  $A$  ( $\text{cm}^2$ ) is active cell's area,  $\sigma$  ( $\Omega/\text{m}$ ) is specific conductivity.

Electric potential varies with the changing of electrolytes' concentration throughout the reaction in

different state-of charge (SOC), which could be illustrated by Nernst Equation:

$$\epsilon_{effective\ rev} = \epsilon_{rev} + \frac{RT}{nF} * \ln\left(\frac{c_{a,p}c_{c,p}}{c_{a,r}c_{c,r}}\right) \quad (8)$$

Also, operating range of SOC could affect the cell's average voltage discharge, with such complexity of output variation, operation and control of vanadium battery appeared hardly to be manipulated. In this study, the effective electric reversible potential in (9) will be assumed in a range of 1.22V – 1.5 V not including losses according to (Yeon et al., 2017) since an addition of SOC modeling would be very time-consuming.

$$\epsilon_{cell} = \epsilon_{effective\ rev} - \epsilon_{act} - \epsilon_{ohm} - \epsilon_{mass} \quad (9)$$

Where  $\epsilon_{cell}$  is the terminal potential of each cell

### 5.2.2 Cost Inventory

In figure X, model's cost is basically divided into power and energy components due to RFB distinctive decoupling features. Power component consists of capitals from cell stacks, fluid regulation, electronic systems, control systems and Assembly, while energy component comprises both the cost from electrolyte and tank storage.

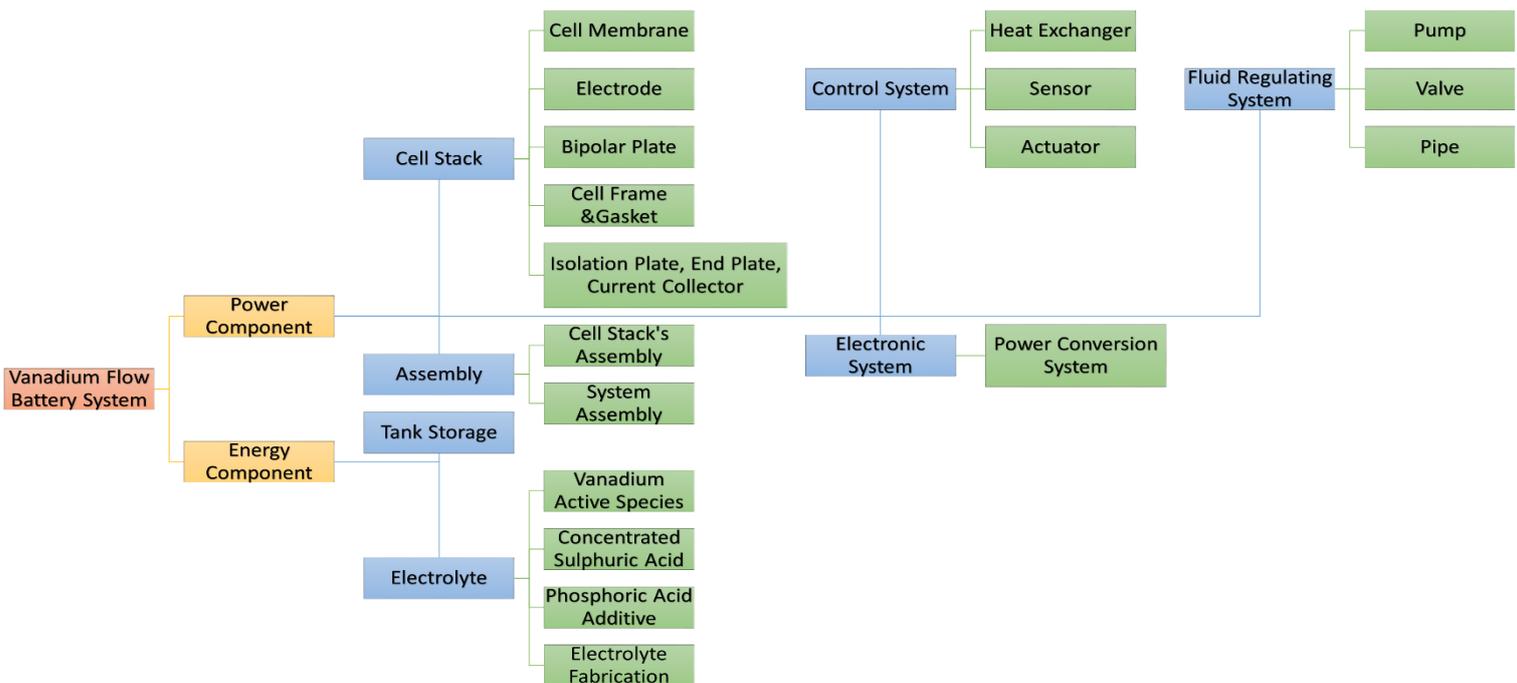


Figure 6 Vanadium flow battery system components chart

## Cost of Power Component

$$C_{power} = C_{cell\ stack} + C_{fluid\ regulation} + C_{electronic\ system} + C_{assembling} + C_{control\ system} \quad (10)$$

Power components scales-up their costs with increasing power which means a larger number of cells or cell stacks, and it is important to figure out the number of cells needed to achieve certain power rating. Relation is written as follows:

$$\bar{P}_{system} = N * \bar{\epsilon}_{cell} * i * A \quad (11)$$

Where  $\epsilon_{cell}$  is the terminal potential of each cell, N is number of cells, I is current density and A is active area.

The Cell stack is in a sandwiched structure with various components placed and compressed in frames. This model assumes every 20 cells will be assembled into one cell stack. Regarding EPRI (2007) and Noack et al. (2016), for each 20-cell stack is composed of 20 ion-exchange membrane, 21 bipolar plates, 40 electrodes felt, gaskets and frames, and 2 end plate, isolation plate and copper current collectors. Assembling materials like bolts and nuts will be scaled in number of stacks instead of cells.

$$C_{cell\ stack} = C_{membrane} + C_{carbon\ felt} + C_{Bipolar\ Plate} + C_{frame} + C_{gasket} + C_{end\ plate} + C_{isolation\ plate} \\ + C_{current\ collector} + C_{assembling\ material} \quad (12)$$

In terms of active area and number of cells,

$$C_{cell\ stack} = NA * c_{membrane} + (N + 1)A * c_{Bipolar\ Plate} + 2NA * (c_{carbon\ felt} + c_{frame} + c_{gasket}) + 2A * (c_{end\ plate} + c_{current\ collector} + c_{isolation\ plate}) + \frac{N}{20} * c_{assembling\ material} \quad (13)$$

Noack et al. (2016) introduced two elements within the cost of material, they are original component cost with material factor €/m<sup>2</sup> and fabrication cost in € per unit. They intended to present a really initiate stage of deployment in vanadium flow battery and tried to simulate the real scenario in experimental lab and pilot plant. They assume some part of the components would be consumed or wasted during fabrication, material factor (*M*) could indicate a real demand of a material.

$$C_{cell\ stack\ material} = M * c_{material\ cost\ in\ \frac{\text{€}}{\text{m}^2}} + N * c_{fabrication\ cost\ in\ \frac{\text{€}}{\text{unit}}} \quad (14)$$

For assembling, the model breaks down the component into stack and system. Assembling involves both the participation of inspecting workers and operating workers with using assembling machines like clamping units. The more number of cells, the more time they need to spend on assembling, resulting in high labour and energy cost.

$$C_{assembling} = C_{Stack\ assembling} + C_{System\ assembling} \quad (15)$$

$C_{Stack\ assembling}$

$$= Time_{hour\ per\ cell} * N * C_{Labour\ hourly\ wages} + E_{Stack\ Assembling\ Energy\ per\ cell} * C_{energy} * N \quad (16)$$

$C_{System\ assembling}$

$$= Time_{hour\ for\ Assembling\ system} * C_{Labour\ hourly\ wages} + E_{System\ Assembling\ Energy} * Time_{hour\ for\ Assembling\ system} * C_{energy} \quad (17)$$

The original models did not design a scale-up relationship for the rest of the components, while in this model, these parameters will be scaled up linearly regard to the power rating.

$$C_{fluid\ regulation} = C_{pump} + C_{valve} + C_{piping} \quad (18)$$

$$C_{electronic\ system} = C_{PCS} \quad (19)$$

$$C_{control} = C_{actuator} + C_{sensor} + C_{Heat\ Exchanger} \quad (20)$$

### Cost of Energy Components

$$C_{energy} = C_{electrolyte} + C_{tank\ storage} \quad (21)$$

For cost of electrolyte:

$$C_{electrolyte} = C_{vanadium\ active\ speices} + C_{solvent} + C_{catalytic\ additive} + C_{electrolyte\ fabrication} \quad (22)$$

Since the cost of electrolyte is in scale with volume, volume represent as:

$$V = \frac{E_{total\ energy}(Wh) + E_{loss\ due\ to\ auxiliary\ and\ control\ service} + E_{shunt\ loss}}{\frac{nFc}{60 * 60} * SoC\ Range * \bar{\epsilon}_{cell}} \quad (23)$$

Where c is molar concentration, SoC range is the operating window as a percentage in the equation.

One part of the energy will be consumed to operate control system, fluid regulation and PCS, another part of the energy will be lost via shunt current. (Tang et al., 2014) compared pump energy

consumption of constant flow rate and variable flow rate, it showed that variable flow rate, which took about 2% of the energy, has more potential on reducing unnecessary pumping energy. For shunt current loss, (Xing et al., 2011) indicate around 1.5% of the total energy would be lost due to current flow through manifold and channels.

According to the procedure of preparing vanadium electrolyte, 1L of vanadium pentoxide solution could produce 1L of catholyte and 1 L of anolyte, yet the original model from Noack et al. (2016) has double counted cost accounted for vanadium active species. This can be verified by the amount of vanadium pentoxide we need for each kWh today. Terry Perles.(2018) mentioned around 10 kg of vanadium pentoxide could store 1 kWh of energy capacity. However, 19.82 kg of vanadium pentoxide was required in the previous models.

Moreover, the storage volume above represents only one tank, in the system, anolyte and catholyte are in two separated tanks, thus, the total volume has to be multiplied by two in order to sum up the cost of solvent, additive and electrolyte fabrication.

$$C_{electrolyte} = V * (c_{VAS}m_{VAS}C_{VAS}) + 2V * (c_{solvent}m_{solvent} C_{solvent} + c_{catalytic\ additive}m_{catalytic\ additive}C_{catalytic\ additive} + c_{electrolyte\ fabrication}) \quad (24)$$

Where m (g) is mass and c (mol/l) is molar concentration

Several cost parameter with different units will be discussed in the finding section. They are power component in €/kW, energy component in €/kWh and system capital cost in €/kWh. As system is highly decoupled in energy and power, such categorization would be more convenient to the following analysing section.

$$C_s = \frac{C_p}{T} + C_E \quad (25)$$

Where T (hr) is operation duration

### 5.3 Main Assumption on Model's Parameter and Scenarios

Vanadium flow battery is a complex system with many components, every part the previous section mentioned is essential to help operate the system. The study would intend to focus on the six components that are dominating within the system price, they are vanadium active species, ion-exchange membrane, electrode felt, bipolar plate, gasket and cell frame; while generalizing other parameters into three different scenarios account for certain degree of cost reduction or improvement in these components.

The research method was initially designed to carry an expert elicitation to seek the views of experts in VRFBs on the potential sources of cost reduction for the six batteries' components to 2030 in a research trip to The International Flow Battery Forum (IFBF 2018) in Lausanne, Switzerland. By inputting their various percentile estimates into the bottom-up models, a more reliable result about future cost could be generated. However, flow battery is a relatively immature technology, the forum was held with an emphasis on study in electrochemistry and more experts were interested in the various mechanism of new type of redox flow battery. Little experts had covered the economic view of vanadium flow battery, not to mention what the future cost of the six components will be. Material suppliers like SGL, OXKEM, The Chemours Company had also attended to the conference, yet due to their companies' interest, they would not release some confidential information such as the degree of reduction in component's cost there will be with a certain amount of order, for academic research purpose unless the customers are certified to ask for quotation. Hence, instead of acquiring

information by constructing structured interview, the study would statistically analyze the historical values for the six main components from prior literatures and some experts at IFBF 2018. Mean value of each set of the data would be inputted according to present and future scenario.

|                                    | <b>Vanadium Species</b> | <b>Ion-Exchange Membrane</b> | <b>Bipolar Plate</b> | <b>Carbon Felt</b> | <b>Frame</b> | <b>Gasket</b> |
|------------------------------------|-------------------------|------------------------------|----------------------|--------------------|--------------|---------------|
| <i>Present Mean Value (€)</i>      | 19.03                   | 377.18                       | 112.68               | 68.21              | 38.72        | 89.60         |
| <i>Present <math>\sigma</math></i> | 10.33                   | 333.94                       | 129.80               | 41.95              | 47.75        | 152.38        |
| <i>Future Mean Value (€)</i>       | 9.55                    | 55.88                        | 42.13                | 24.01              | 1.72         | 4.66          |
| <i>Future <math>\sigma</math></i>  | 4.62                    | 49.87                        | 53.59                | 21.37              | 1.13         | 4.54          |

Table 12 Present and future cost and sigma of six main components

One present and two future scenarios are created to compare the variation of system costs. Considering the fact that Noack et al. (2016) had employed high initial costs input into their bottom-up model, in future conservative scenario, most of the components' costs are reduced by 50% and in future optimistic scenario, by 75%. Notably, the average voltage increases in the future since vanadium expert, Mr. Terry Perles (2018) predicted there would be improvement on utilization of vanadium by implementing a better control and fluid regulating system. He continued, the conversion cost to transform  $V_2O_5$  to electrolyte currently would be about \$1.25/pound, if assuming 1.6 M of vanadium electrolyte solution is used, the electrolyte fabrication cost would be about 0.65 €/ Litre, thus we anticipate a further reduction in this value in an optimistic scenario. Also, material factor will be 1, and there will be no fabrication cost in the future since the material suppliers will provide component in tailor-made size and structure that helps cell assembly.

| <b>Other Parameters</b> | <b>Unit</b>      | <b>Present</b> | <b>Conservative 2030</b> | <b>Optimistic 2030</b> |
|-------------------------|------------------|----------------|--------------------------|------------------------|
| Power Rating            | kW               | 500            | 500                      | 500                    |
| Current Density         | A/m <sup>2</sup> | 500            | 500                      | 500                    |
| Area                    | m <sup>2</sup>   | 0.0980         | 0.0980                   | 0.0980                 |
| SOC                     | %                | 60%            | 60%                      | 60%                    |

|                                |                  |      |       |        |
|--------------------------------|------------------|------|-------|--------|
| Average Input/ Output Voltage  | V                | 1.12 | 1.27  | 1.43   |
| Current collector              | €/m <sup>2</sup> | 700  | 350   | 175    |
| Isolation plate cost           | €/m <sup>2</sup> | 300  | 150   | 75     |
| End plate cost                 | €/m <sup>2</sup> | 600  | 300   | 150    |
| Fabrication Cost               | €/unit           | 5    | 0     | 0      |
| Material Factor                | €/unit           | 1.5  | 1     | 1      |
| Stack assembling man hour      | h/cell           | 0.3  | 0.15  | 0.075  |
| Man hour cost                  | €/h              | 30   | 40    | 50     |
| Additional assembling material | €/stack          | 20   | 10    | 5      |
| Stack assembling energy        | kWh/cell         | 0.3  | 0.15  | 0.075  |
| Energy cost                    | €/kWh            | 0.3  | 0.4   | 0.5    |
| PCS cost                       | €/kW             | 500  | 250   | 125    |
| Heat exchanger cost            | €/kW             | 150  | 75    | 37.5   |
| Pump cost                      | €/kW             | 100  | 50    | 25     |
| Piping cost                    | €/m              | 20   | 10    | 5      |
| Valve cost                     | €/kW             | 3    | 1.5   | 0.75   |
| Actuator cost                  | €/kW             | 33   | 16.5  | 8.25   |
| Sensor cost                    | €/kW             | 25   | 12.5  | 6.25   |
| System assembling man hour     | h                | 300  | 150   | 75     |
| System assembling energy       | kWh/h            | 1    | 0.5   | 0.25   |
| Tank cost                      | €/L              | 1.1  | 0.275 | 0.1375 |
| Electrolyte production cost    | €/L              | 2.5  | 0.65  | 0.3125 |
| Cell Stack                     | Unit             | 455  | 400   | 357    |
| Cell                           | Unit             | 9100 | 8009  | 7151   |

Table 13 Input parameters of present, future conservative and future optimistic scenario

## 6. Result

### 6.1 Detailed Investigation: 500 kW All-Vanadium System

The bottom-up model generated 1-hour, 8-hour, and 24-hour 500kW All-Vanadium System with inputs from three different scenarios: Present, future conservative and future optimistic. For each scenario, there are figures that compare the total system capital cost, power components cost breakdown and energy components cost breakdown embedded in system cost breakdown.

#### 6.1.1 Present Scenario

As shown in figure 7, the system capital cost decreased with systems in a larger energy capacity, reducing 79% and 87% of the 1-hour system capital cost in 8-hour and 24-hour cases. Little capital cost research has been done in both 1-hour system and 24-hour systems, but for 8-hour systems, result of 1067 €/kWh in system capital cost seemed inconsistent with estimations from EPRI.(2007)(452 €/kWh) and Minke et al. (2017)(520 €/kWh). This discrepancy could be attributed to high initial cost input and additional cost related to material factor and fabrication cost in cell stacks in Noack et al.,(2016)'s model.

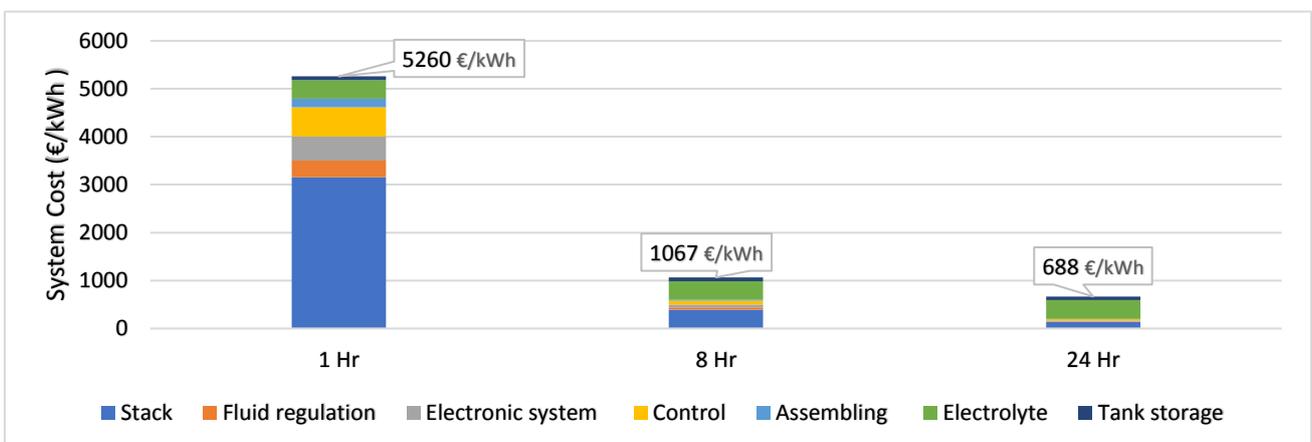


Figure 7 Present System Capital Cost in 1,8 and 24-hour (500kW) system with power component 4792 €/kW and energy

component 468 €/kWh

In the power component breakdown, figure 8, the five components of interest dominated the majority of share in cell stack's cost. Different from Noack et al. (2016), gasket in the model was less notable because the mean value of gasket cost regarding previous literature is used instead of the high gasket cost input in Noack et al. Also, unlike to the identical share of felt and bipolar plate in 19% at the cell stack cost breakdown in EPRI,(2007), the characteristic of felt having more repeating units resulted in a higher fabrication and material cost, although the cost input of BPP is higher than that of carbon felt.

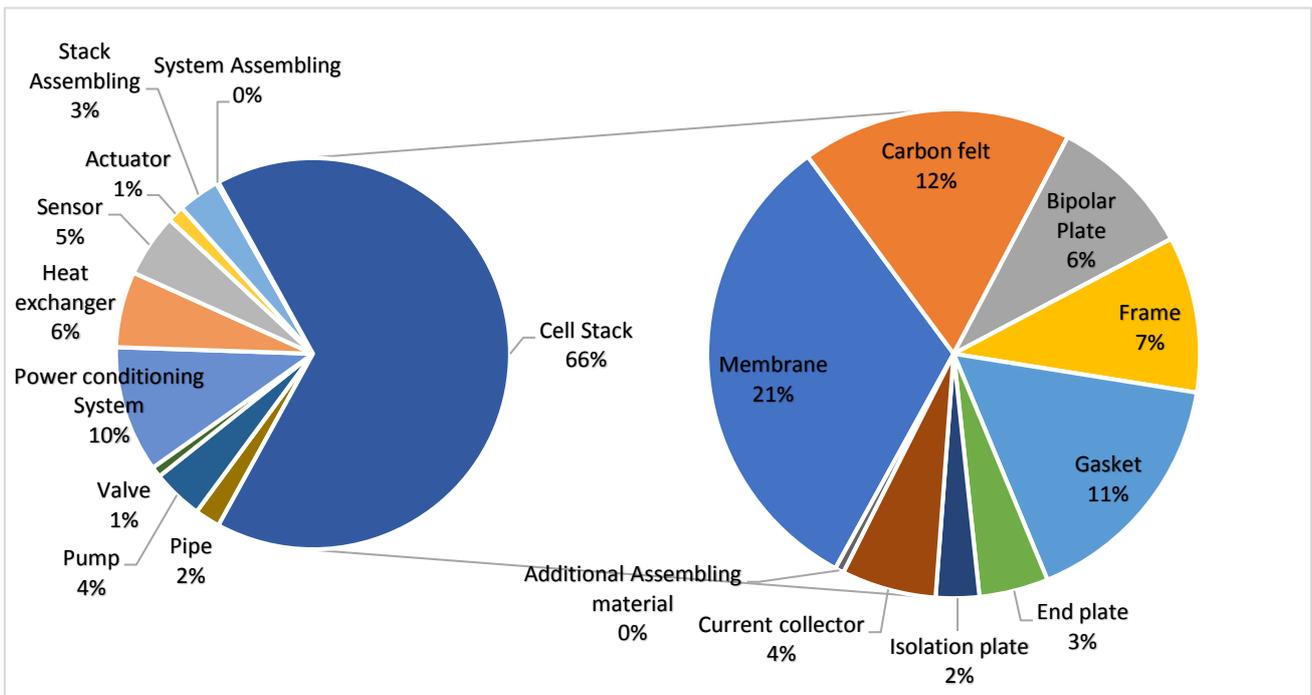
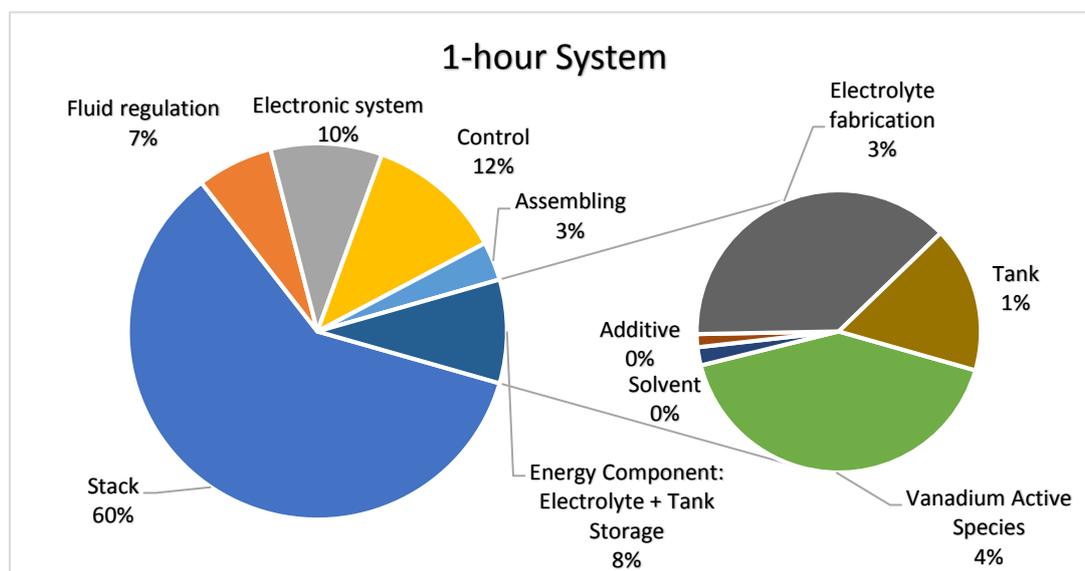


Figure 8 Power Component breakdown of 1,8,24-hour systems in the present scenario

Figure 9 shows how costs are broken down to different components in 1,8,24-hour systems. It is apparent from this figure that blue section which represents cost of cell stacks dropped significantly from 1-hour system to higher-hour system, while shares of energy components increased from 8% to 70%. With the information from the figure of power component breakdown, the cell stack cost is 3162.72 €/kW, appeared much lower than the cell stack cost of 5265 €/kW from Noack et al. (2016).

The closest value of 2687 €/kW was from Li et al., (2017), it had divided VRB into three different qualities, which the comparable figures, 2687 €/kW of cell stack was categorized as the highest level in starting material qualities that had the best efficiency and longest service time more than 20 years. However, prior literature seldom specified the quality of materials in their list, thus, we conjectured the components the model inputted were in high quality. For 8-hour VRFB's system, EPRI. (2007) showed a close added percentage of 19.3% for control (Power Conditioning System), electronics system and fluid regulation system to this study's result 17%, also, cell stacks and vanadium electrolyte in EPRI. (2007) were each 10% less than current result. It is difficult to explain this result, but it might be related to the different system boundary of the two models, EPRI. (2007) was more concerned with the profit and balance of plant. For 24-hour VRFB's system, about 3/4 of the share was taken by energy components. Also, in all scenarios, the energy components consists of two big portions of raw material cost of  $V_2O_5$  and its fabrication cost, which finding reflect those of Noack et al.(2016) who also found that cost of electrolyte fabrication is comparable to that of vanadium active species.



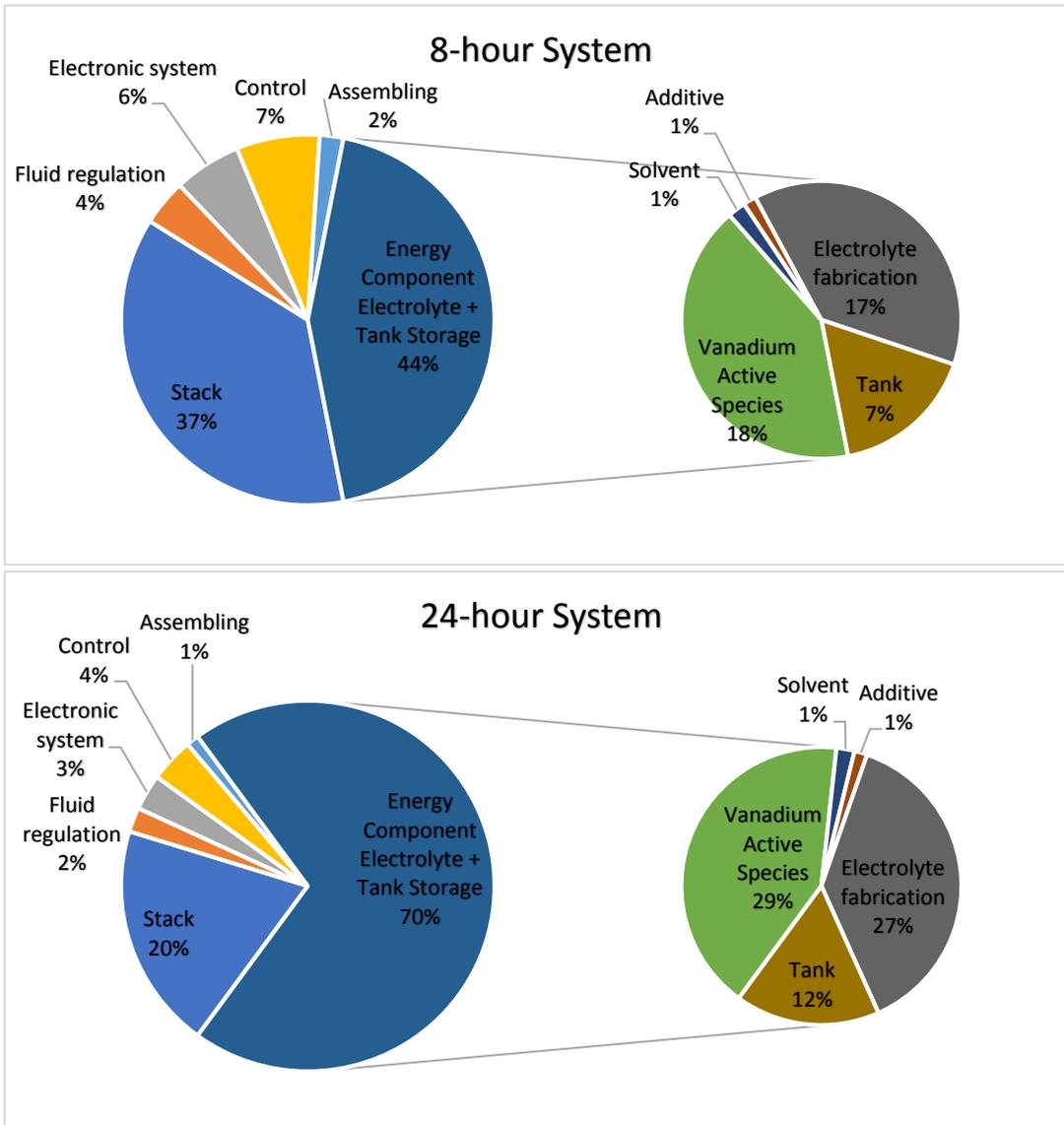
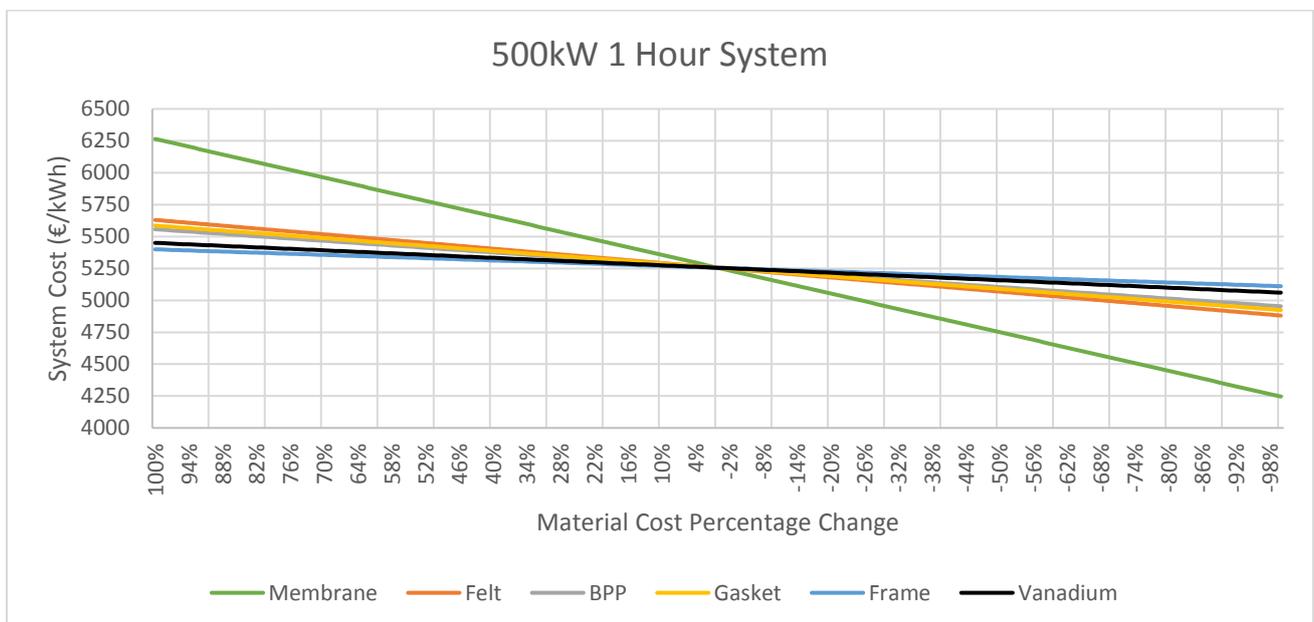


Figure 9 Comparison of present capital system cost breakdown in various hour-systems

### 6.1.1.1 Sensitivity Analysis

To compare how different value changes in individual material cost will affect the total system capital cost in the present, sensitivity analysis has been carried as below. Figure 10 shows the intercorrelations of the materials price change with respect to system price variations. From the graph below we can see that, the cost influence that the cell stack's component brings is always in the following order: membrane, carbon felt, gasket, bipolar plate and cell frame. However, the energy component, the impact of vanadium active species varies between different duration systems. Also, system capital cost decreases in a battery system with longer duration since the cheaper energy

component dilutes the overall cost. Membrane is the most influential component in a 1-hour system, its material cost change could bring almost € 2000/kWh ( $\pm 18.9\%$ ) variation on system cost; while vanadium lies between cell frame and bipolar plate. In an 8-hour system, vanadium active species with € 388/kWh ( $\pm 18.2\%$ ) variation supersedes membrane with only ( $\pm 11.7\%$ ) on system cost. In a 24-hour system, the effect of price change in membrane is insignificant to the overall capital cost, but vanadium is able to lead to a total cost in variation of  $\pm 25.2\%$ . This trend is consistent with that of Minke et al. (2017) which assessed the sensitivity of four components: membrane, electrode, bipolar plate and electrolyte. Compared to their sensitivity graph with VRFB system in 10 MW – 80 MWh system with our 8-hour 500kW system, their system capital is only 500 €/kWh which is not comparable to our value of 1068 €/kWh although the cost input value is similar. The inconsistency may be due to the 1.5 material factor and fabrication cost in this model as a result of such big difference in system cost. This also leads to the fact that the sensitivity of cell stack's components of their models appears much less than ours.



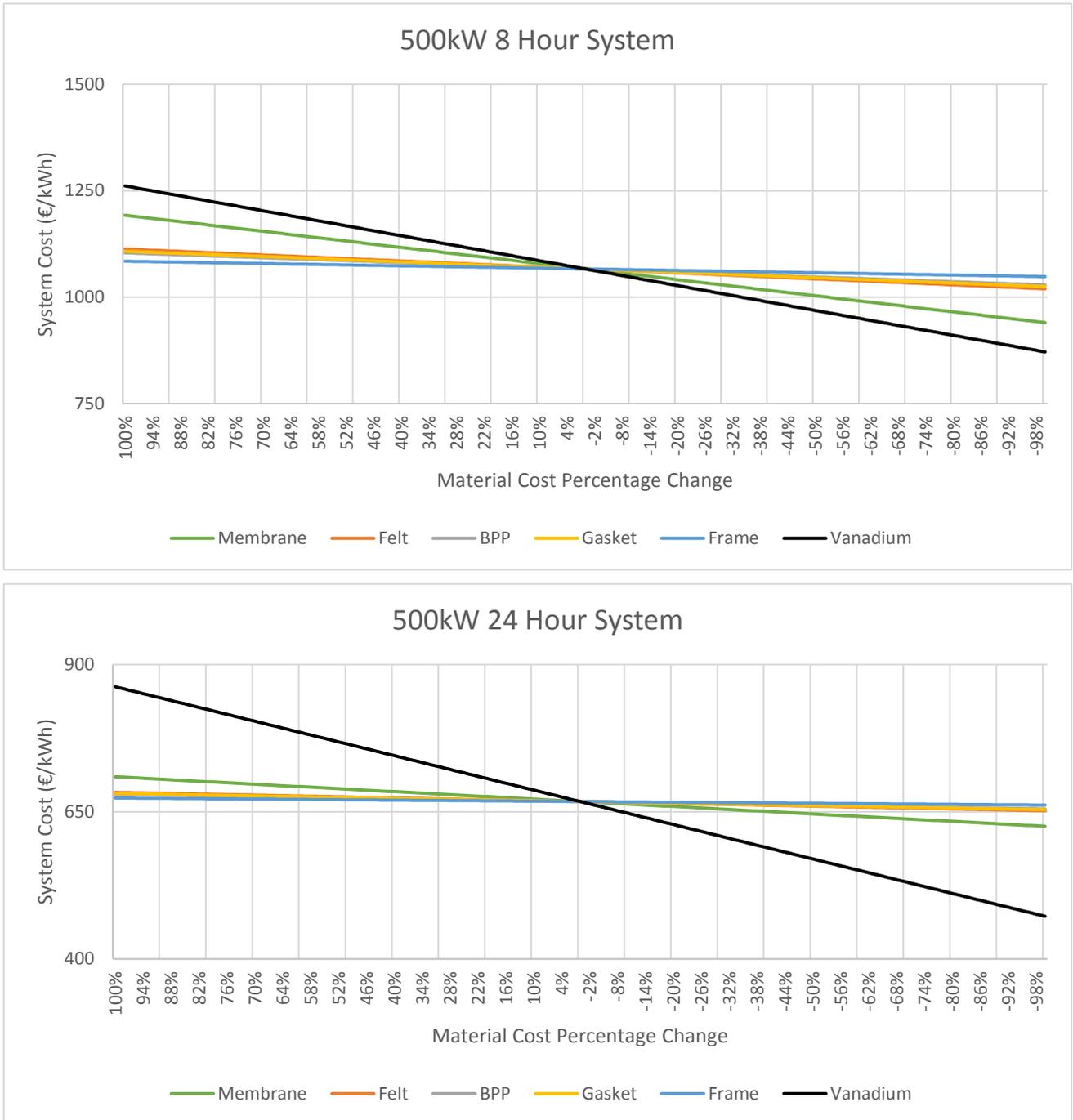


Figure 10 Sensitivity analysis of six main components of various hour-systems in the present scenario

### 6.1.2 Future Conservative Scenario

Under the scenario with 50% cost reduction in the parameters other than the six components of interest, what stands out in the figure is, the system capital cost in 1-hour system had significantly decreased from the present scenario, 5260 €/kWh to 1408 €/kWh. The power component's cost and the energy component's cost were reduced to almost 1/4 and 1/3 of the original value in present

scenario, 1256€/kW and 153 €/kWh respectively. The more than half reduction of both indicators manifested even a greater effort from the six components driving down the system's cost. For 8-hour system, our system capital cost 310 €/kWh sit between the estimations from EPRI.(2007) 401.25€/kWh and Minke et al. (2017),186€/kWh.

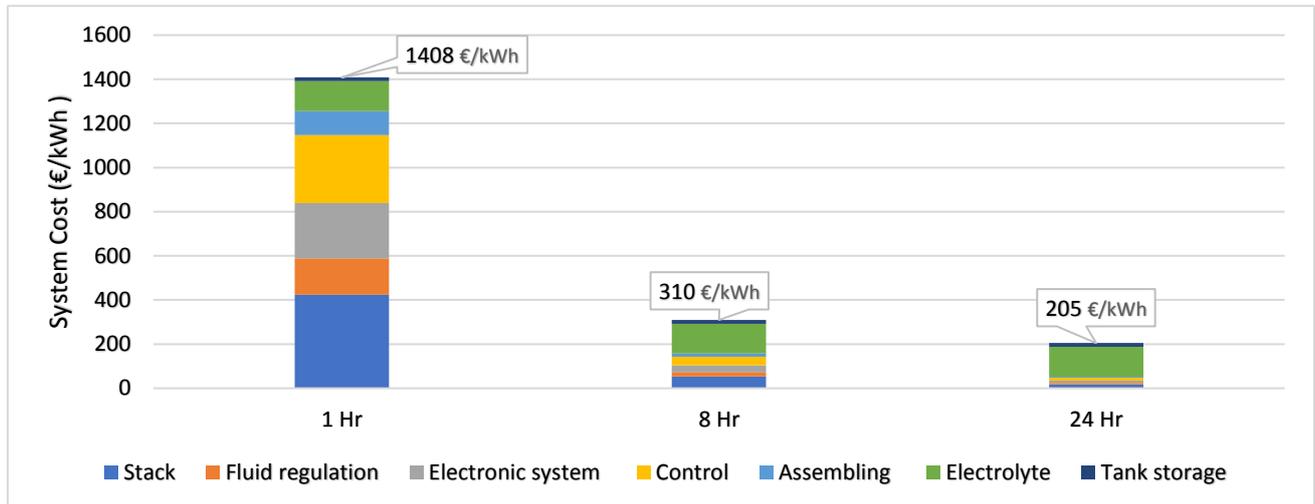


Figure 11 System Cost of 1,8 and 24-hour (500kW) system in Future Conservative Scenario Power Component: 1256 €/kW, Energy Component: 153 €/kWh

The most intriguing aspect of figure 12 in this breakdown is that the cell stack had tremendously shrank its sizes in the pie chart. Three possible drivers may explain this observation. First, cheaper cost of the components such as membrane, felt, etc. benefit from economy of scales and greater deployment of vanadium flow batteries (Minke et al., 2017, 2016; Minke and Turek, 2015); Second, in the future scenario, there is no fabrication cost, and the corresponding material factor is 1 as suppliers would provide a more assembling-friendly components without unnecessarily wasting materials; third, the increase of average voltage helps reducing about 12% (55) of the number of cell stacks. Notable in the cell stack's breakdown is the comparable share of copper current collectors to membrane's and felt's. Although every cell stack only has two pieces of copper current collector, it has a relatively high initial cost.

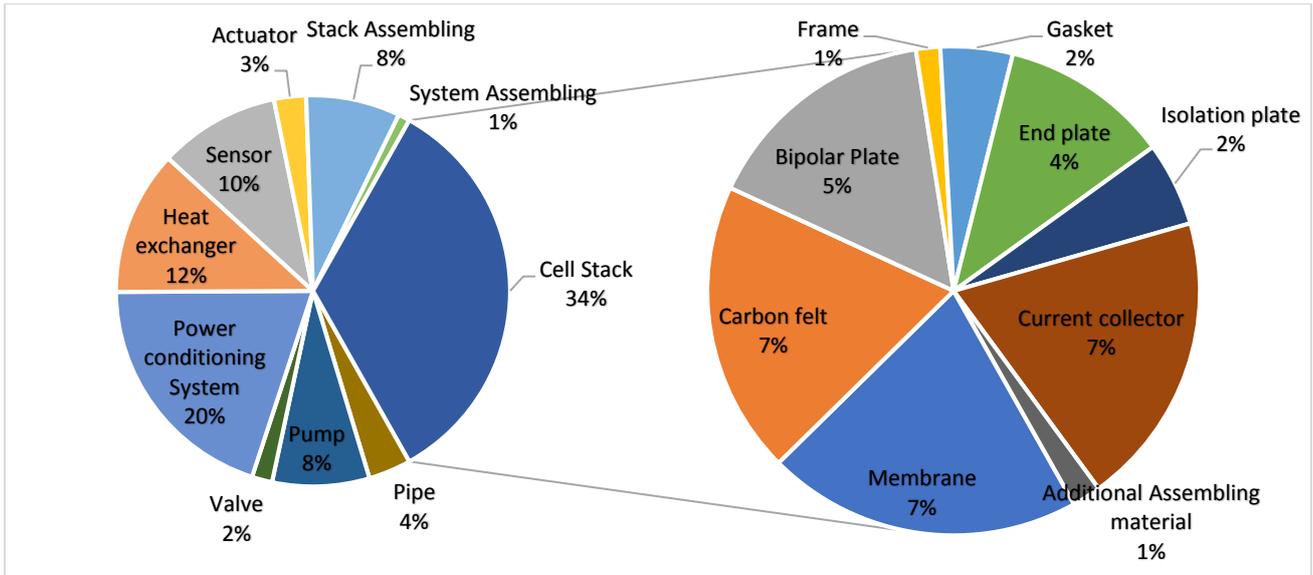
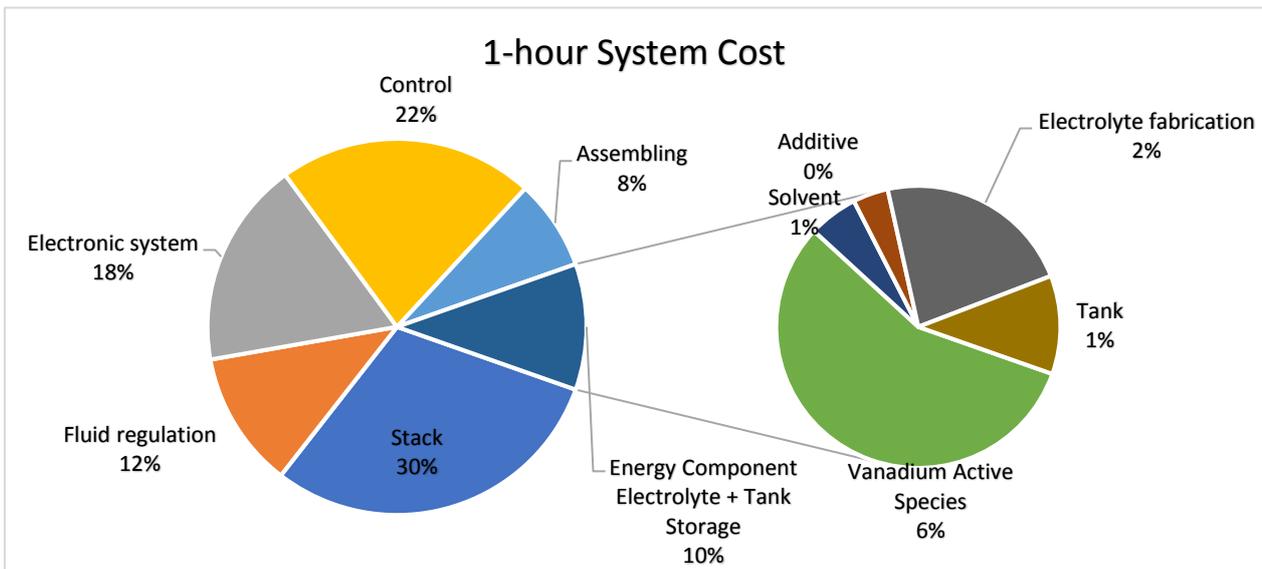


Figure 12 Power Component breakdown of 1,8,24-hour systems in the future conservative scenario

Again, the shares movement was similar to the present scenario in different hour systems. Closer inspection of the figures 12 and 13 showed the power component cost of cell stack was about 376.8 €/kW which was still higher than the value of 239.76 €/kW from EPRI. (2007) because the material cost input of cell stack in EPRI. (2007) was much lower than ours. Besides, raw material cost of vanadium active species ( $V_2O_5$ ) had more than 50% shares within the energy component breakdown compared to the present scenario since a more down-to-earth electrolyte fabrication cost obtained from Perles (2018) instead of the sky-high price from Noack et al. (2016) is used in the future conservative case, thus the share of vanadium pentoxide even expanded more.



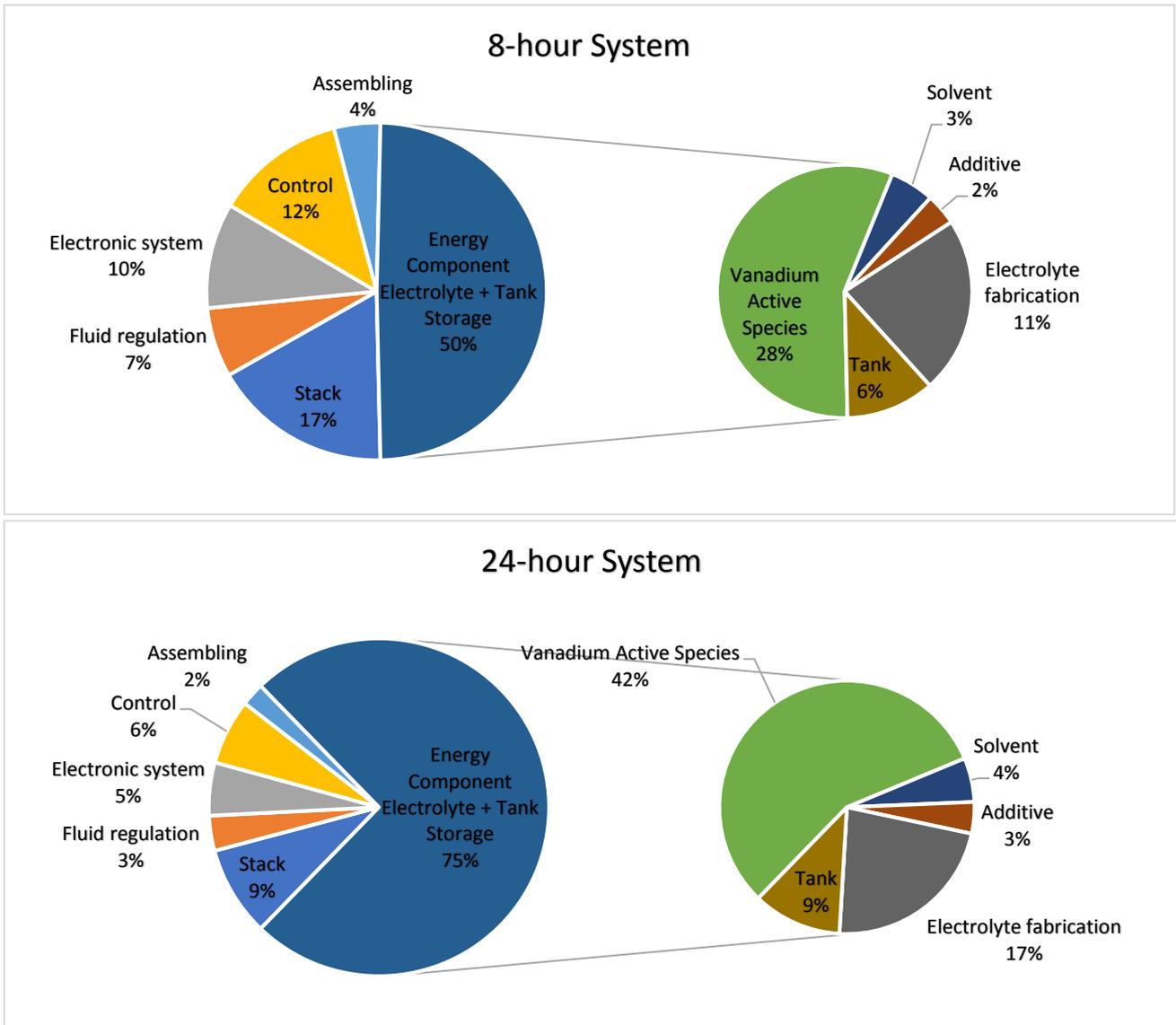


Figure 13 Comparison of future conservative capital system cost breakdown in various hour-systems

### 6.1.3 Future Optimistic Scenario

A further 25% cost reduction took place in the future optimistic scenario while the six parameters of interest remained the same as future conservative case. All the system's costs are approximately reduced 80% of the original cost in the present scenario. The 8-hour system cost ,207 €/kWh is now nearby to the result from EPRI. (2007),186€/kWh. However, the lowest possible cost 146 €/kWh in 500kW system appeared not as the lowest candidates among the previous literatures. Despite the smaller 4-hour system in energy capacity in Viswanathan et al. (2014), the predicted cost could already go as low as 136 €/kWh; Darling et al (2014) indicated even lower possible cost input of

vanadium active species as 5.2 €/kg and BOP (components other than cell stack, for example, Control system, electronic system and fluid regulation system) as 109 €/kW, compared to our input 9.55 €/kg and 426.3 €/kW to bring about system cost of 88 €/kWh.

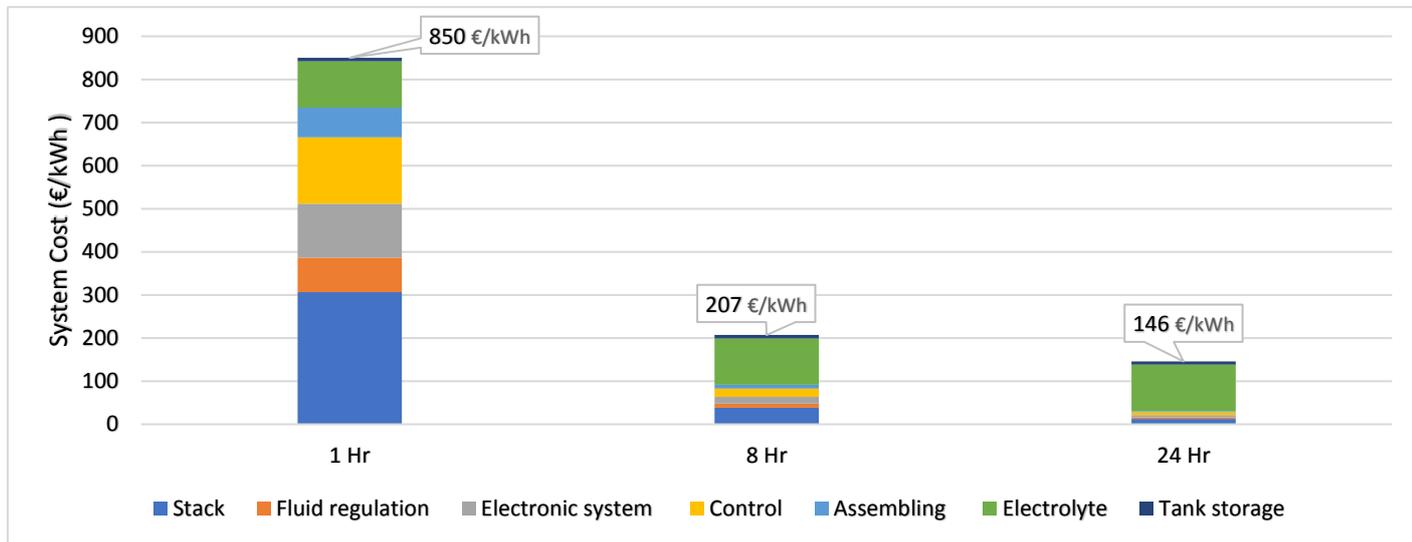


Figure 14 System Cost of 1,8 and 24-hour (500kW) System in Future Optimistic Scenario Power Component: 735 €/kW, Energy Component: 115 €/kWh

Share of cell stacks re-achieved back to 40% from 30% due to the extra 25% cost reduction on other parameters. Due to a further increase in average voltage, 43 more cell stacks were eliminated in the future optimistic scenario, resulted in 10% cost reduction in cell stacks. The power component cost of stack was around 308 €/kW.

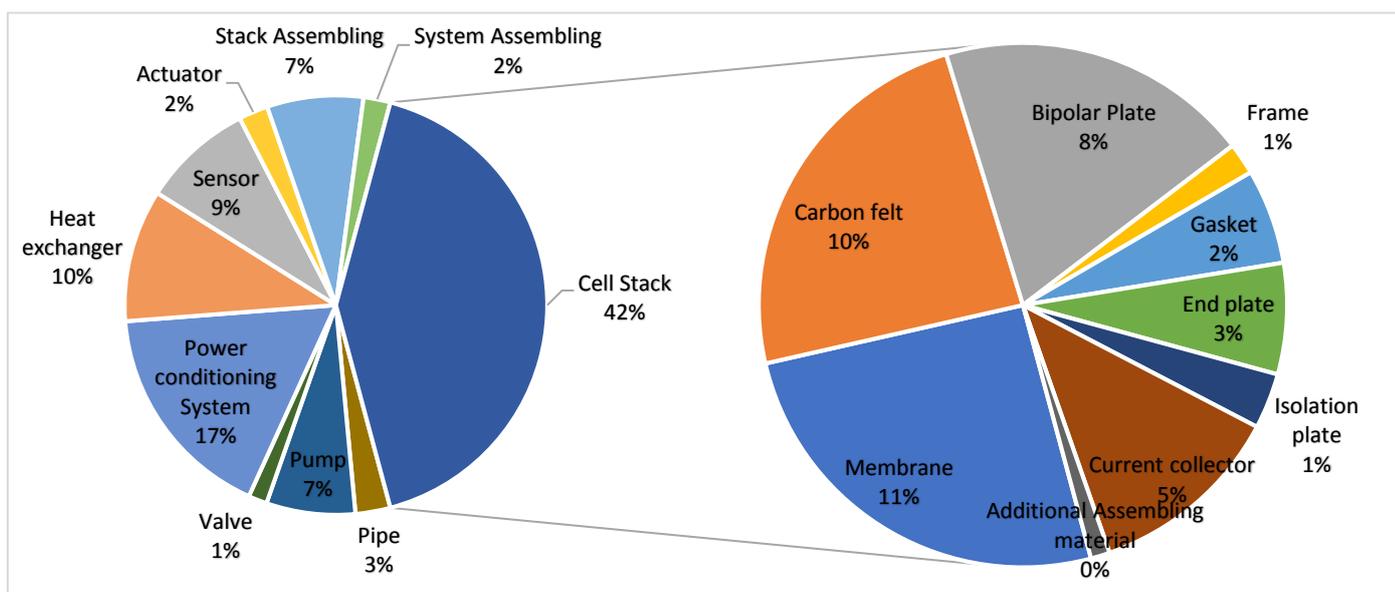


Figure 15 Power Component breakdown of 1,8,24-hour systems in the future optimistic scenario

The system cost of future optimistic scenario has a rather similar breakdown to the future conservative case, which share of energy components expanded with systems in a larger energy capacity. The reduction of energy component cost from the conservative 153 €/kWh to the optimistic case 115 €/kWh was not as apparent as power component cost from 1256€/kW to 735 €/kW.

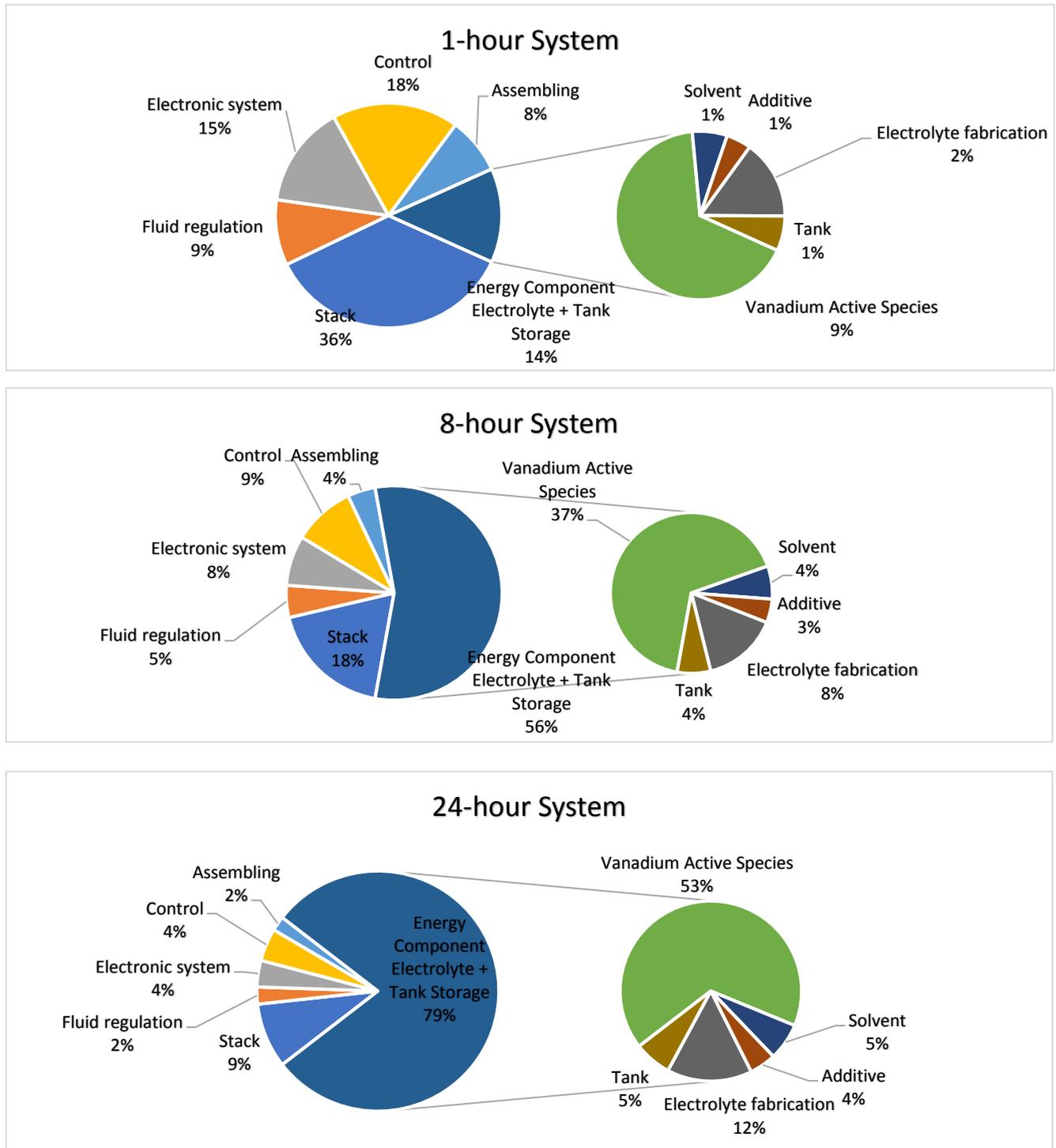


Figure 16 Comparison of future optimistic capital system cost breakdown in various hour-systems

### 6.1.4 Relationship of System Capital Cost against Duration and Power Rating

A smoother trend line has been plotted to show how system costs varies in different hour-systems under the three scenarios. Flow battery has the advantage of having a lower system cost in a high-hour system. In every scenario, the steepest drop of system cost took place at E/P 1 to 2, and the system capital cost went steady with a higher hour-battery. Notice that the system cost would not fall below the energy component cost in systems with infinite large energy capacity. For the figure below, it showed how the system costs varies in different power rating. The steady trend line from 110kW to 1000kW implied the system is barely benefitting from economies of scales, which should be considered as further work.

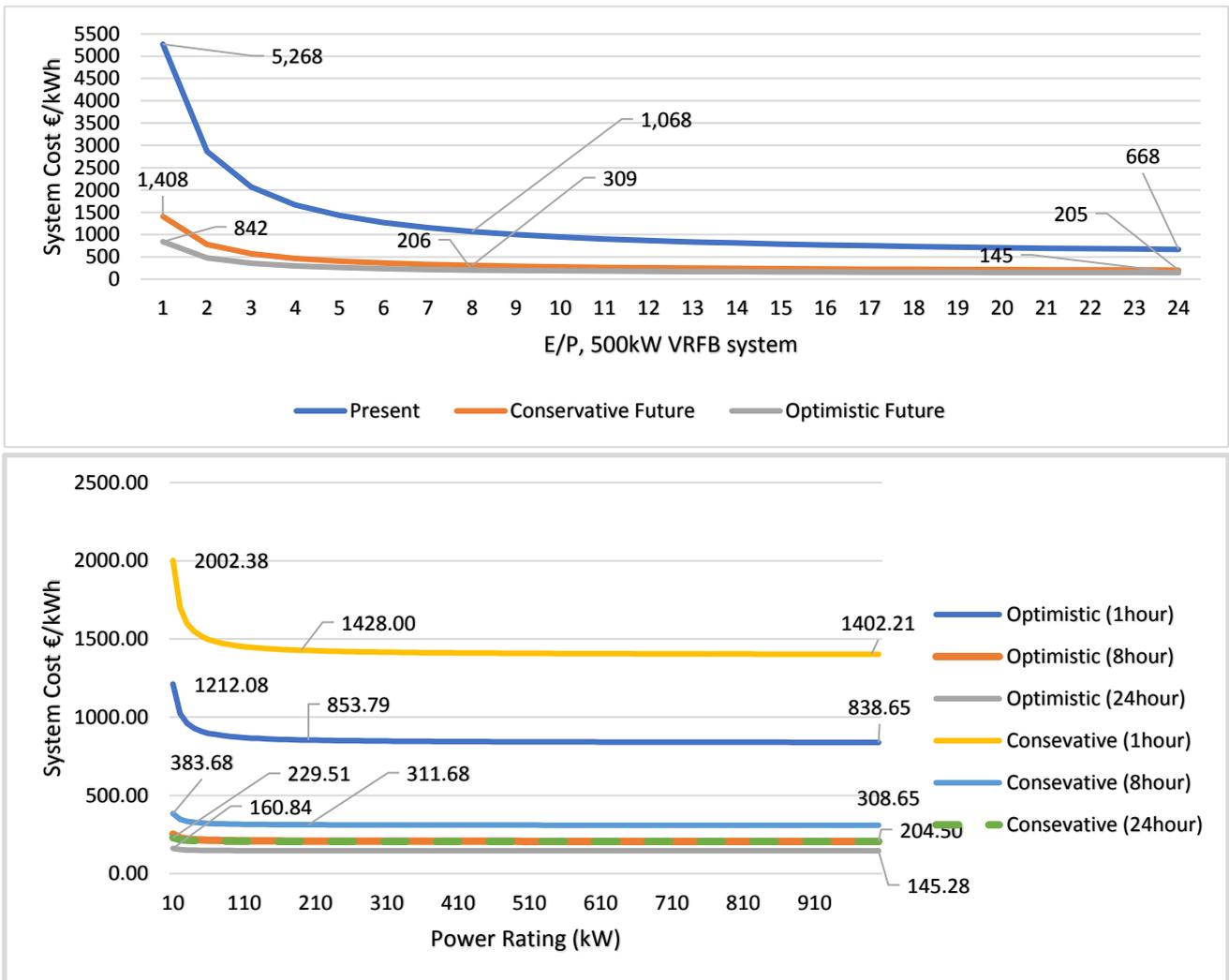


Figure 17 Relationship of System Capital Cost against Duration(E/P) and Power Rating

## 6.2 Monte Carlo Analysis

Considering the fact that the information for the six parameter of interest appears as statistical ranges, instead of mean values as individual input, a Monte Carlo analysis would be helpful to examine every cost possibility in range to compute a distribution of potential VRFB cost. However, as VRFB is highly decoupled in energy and power, system capital cost could vary with different configurations. To figure out a more representative system with a specific size as our investigation target in Monte Carlo analysis, statistic of electrochemical storage was gathered from the DOE Global Energy Storage Database. In figure X, we could observe a bimodal distribution at 1-hour and 4-hour; while in figure X, median value for power rating belonged to category of 500kW. Since VRFB has a system cost advantage in batteries with larger energy capacities, a 500kW, 4-hour system would be selected in the analysis.

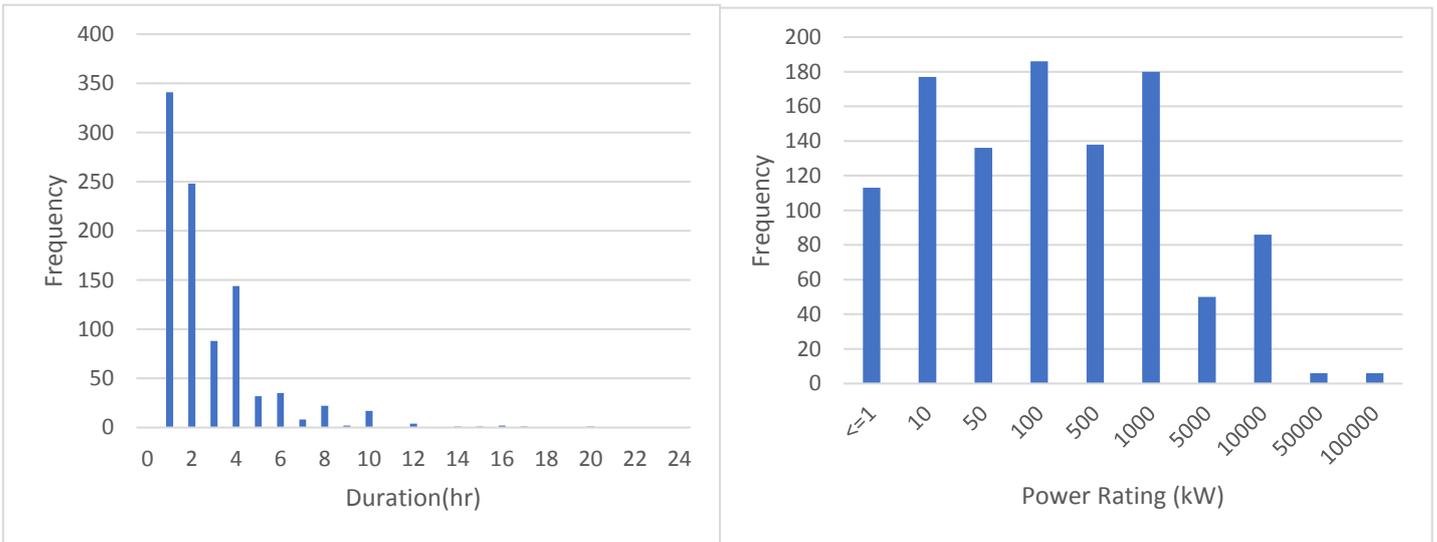


Figure 18 Statistics from Energy Storage Exchange (“DOE Global Energy Storage Database,” n.d.) Number of electrochemical storage system in various duration(left), Number of electrochemical storage system in various power rating (right)

As the historical prices of components were highly uncertain in a large number of sigma shown in table X, to avoid negative number and extreme values, normal distributions with lower and upper 80% interval will be employed to the six main components. Figure XY showed the outcome of Monte Carlo analysis in the present scenario and future scenarios. The analysis for present scenario resulted in a

median cost 1700 €/kWh, with interquartile range 1600-1850 €/kWh. This system cost is somewhat counterintuitive, it is about 3 times to 4 times of the 4-hour system's cost in the previously stated study. This result may be explained by two factors, Material factor and fabrication cost had a significant influence on the present cost; the initial low average voltage output led to higher cell stack cost. While in future conservative and optimistic cases, median values are 460 €/kWh and 295 €/kWh with interquartile range 435-490 €/kWh and 270-329 €/kWh respectively. Although the cost value did not drop below estimation from Viswanathan et al. (2014), 136.4 €/kWh, the result was comparable to 285 €/kWh Minke et al. (2017). Based on the bimodal distribution of future scenario, we would anticipate the future 500kW 4-hour system cost would be between 200 to 545 €/kWh depending on the scale of deployment.

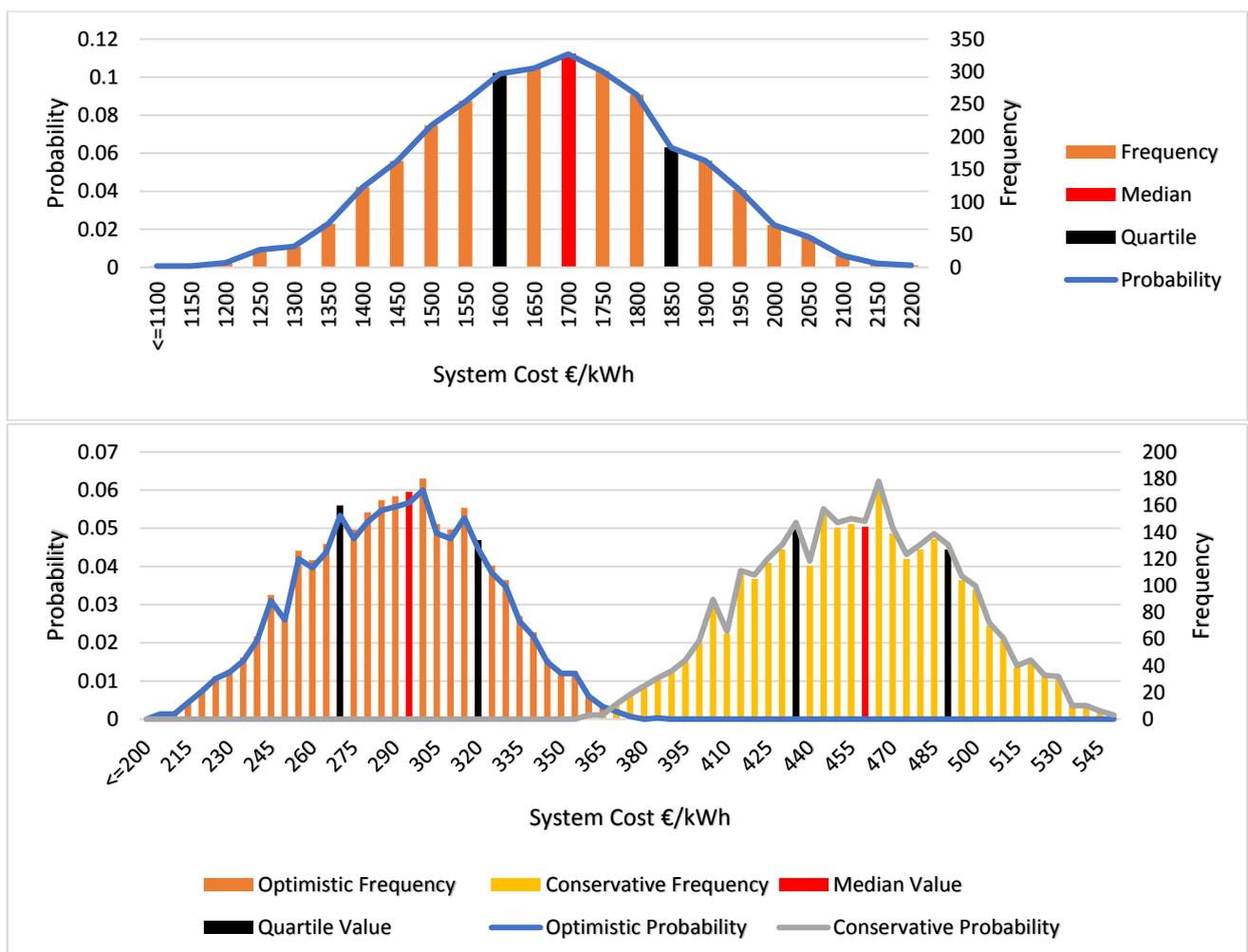


Figure 19 Monte Carlo analysis in different scenarios: present scenario (top), future conservative and optimistic (bottom)

## 7. Discussion

The analysis identified multiple critical determinants of future vanadium flow battery cost: the six main component's cost, energy to power ratio and the type of future scenarios. The costs of five power components: Membrane, Electrode Felt, Bipolar Plate, Gasket and Frame are very influential in a high power-rating system. Regarding previous literatures, these components have a high dependency on economy of scales due to the repeating characteristic of a cell. SGL, (2018) and Minke et al. (2015,2017) both suggested components' cost could be reduced by higher production rate in a logarithm relationship, and the higher production rate referring here could be achieved by a more sophisticated manufacturing technique that might involve automation and larger industries with greater quantities of manufacturing machines. Also, the detailed finding from James et al. (2017) in study of mass production of fuel cell is highly correlated to the case of VRFB because of the similar structure and components of the cell stacks. This governmental study from the U.S. demonstrated a parallel study that a fuel-cell cell stack's cost could experience a steep 70% drop from 79.9 to 22.83 €/kW, when annual production rate increased from 1000 systems to 10000 systems in 2025. Assuming our model in the optimistic scenario (500kW, 7151 cells) was using the same cell stack component the fuel-cell study employed, considering the fact that 114 kW gross power only required 370 fuel cells from Toyota documents (James et al. 2017), the vanadium cell stacks needs about 4.4 times the materials in fuel cell stacks, as a result of  $(79.9 \times 4.4) = 351.56$  €/kW and  $(22.83 \times 4.4) = 100.45$  €/kW in annual production rate of 1000 and 10000 systems respectively. This former power component cost of stacks appears comparable to the previous result in future optimistic scenario (308 €/kW), and it suggested that there might still be a lot of opportunities to reduce the stack cost with a larger industry scale.

For vanadium active species, the present raw material cost 19.03 €/kg dropped to the future cost 9.55 €/kg, in terms of energy component cost, from 194 €/kWh to 77 €/kWh. It is observed that the drop of

material cost is relatively smaller than that of energy component cost, this inconsistency is due to the higher average voltage in future scenario than present scenario, resulted in less electrolyte needed for each kWh in future case. Considering the second factor, energy to power ratio, the higher the energy capacity the system has, the higher the shares of energy components in the system cost. We observed the VRFB systems is growing larger these decades, from kW system to hundred MW system in Dalian(Weaver, 2017). One of the largest German energy group even has been developing a GW size of cavern-flow battery for seasonal storage of photovoltaics systems (EWE GASSPEICHER GmbH, 2018). This trend suggests the vanadium system capital cost would gradually have a greater dependency on cost of vanadium active species. The cost of vanadium pentoxide has been associated with its material supply and production cost. Although Mr. Terry Perles, (2018), the expert of vanadium market, feels optimistic about sufficient vanadium replenishment from primary ore in avoidance of fluctuated market price of vanadium, the future remains highly uncertain. To encounter vanadium high volatility risks, VANITEC, (2018) introduced the idea of leasing vanadium in storage applications. The business model appears pretty logical because the vanadium is not consumed but rather it can be reused when the battery is decommissioned. The vanadium producers could sell vanadium to financial intermediary to be used in leasing arrangements, then the VRFB producers could rent vanadium active species with periodic payments. If we assume leasing of the vanadium, except for a small part of initial cost needed to purchase tank storage, the capital cost for the energy component could completely go away and be replaced by an annual lease payment. Regarding Mr Terry Perles, the oil refining industry platinum group metals used as catalyst are normally leased with lease rates today ranging from 2% to 5%. Assume a 5% annual lease rate for electrolyte. In the future optimistic scenario, the upfront capex for energy components excluded tank storage, would be eliminated, instead, there will be an extra operation cost of  $(107 \times 0.05) = 5.35 \text{ €/kWh}$ . If the battery is cycled 365 times a year, this means the cost of electrolyte is  $(5.35/365) = 0.0147 \text{ €/kWh}$  per year. With the risk transferring to financial intermediary, this could encourage the VRFB developer to invest and commercialise VRFB.

If we combine both efforts from mass production of cell stacks and leasing electrolyte, the total system cost will only consist of power components with a small fraction of energy related component - tank storage. Speaking of a 500kW 4-hour system in conservative future, the power component cost and energy component cost would be around 1180.52 €/kW and 18.36 €/kWh respectively, resulted in system cost of 313.49 €/kWh; While in the future optimistic scenario, the power component cost and energy component cost would be around 530 €/kW and 7 €/kWh, thus, the system cost could be reduced to as low as 139.5 €/kWh.

The current study found that a considerable variation in system capital cost is created in different future scenarios which were an assumption that balance of plant (BOP) would also experience a certain degree of cost reduction. Between the scenarios, the power component cost and energy component cost dropped from 1256 €/kW (Conservative) to 735 €/kW (Optimistic) and 153 €/kWh (Conservative) to 115 €/kWh (Optimistic) respectively. In figure X, we could observe the difference of system capital cost reduced when the energy to power ratio was increasing, from 566 €/kWh at 1-hour, to 103 €/kWh at 8-hour, to 60 €/kWh at 24-hour. As the study assumes the real future scenario might lie between these two scenarios, this finding appeared really interesting and suggested that a larger system in energy capacity have a lower system cost with a narrower potential range, showing the third determinant- type of scenario is less influential to the cost of large system. However, unlike cell stacks and vanadium active species, little literature questioned how balance of plant offered a radical change for system capital cost reduction.

An initial objective in the project was to examine the competitiveness of vanadium flow battery between the electrochemical storages in terms of cost. In the Monte-Carlo analysis, the figure 19 demonstrated a bimodal possibility distribution of the present and future cost of a 500kW 4-hour VRFB system. The median values of VRFB system cost for present, future conservative and future optimistic

scenario are 1700 €/kWh, 460 €/kWh and 295 €/kWh accordingly. In reviewing Schmidt et al.,(2017) ,which studied the future cost projection of various electrical energy storage based on experience curves, the present values of vanadium redox-flow was about 1078 €/kWh , considering the fact that the global cumulative capacity of vanadium flow system has reached 196 MWh. The initial higher value in our study is foreseeable due to the additional fabrication cost and material factor in the present scenario. However, we could trace back and conjecture the corresponding cumulative capacities and years in the two future scenarios. For conservative future, the 460 €/kWh system cost correlated with around 50 GWh cumulative capacity in 2022; for optimistic future, the 295 €/kWh-system located around 600 GWh cumulative capacity in 2030.

Among all electrochemical storage technology for stationary system, without considering cost influences from mass production and leasing electrolyte, vanadium flow battery appears as the cheapest option in both scenarios. Although fuel cell's cost had already been caught up with VRFB's in 100 GWh cumulative capacity and dropped even further than VRFB's in 600 GWh, fuel cell could not form electrical energy storage without electrolysis systems which help convert back and forth between electricity and hydrogen gas; which the combination of the two systems' cost resulted in much higher than VRFB's. Lithium-ion battery had an early predominance in battery market, successfully overtaking lead-acid system, yet in long-duration stationary storage, appeared less attractive to vanadium flow battery due to weaknesses such as cycle-life degradation and self-dissolution in long-duration system("Is Lithium-Ion unassailable in stationary energy storage markets?," 2017). These disadvantages left an opening for VRFB competitors. Recently, the R&D found that lithium titanite (LTO) potentially possesses a long cycle life with around 1.45 times of vanadium battery's (IRENA, 2017). Its future projection cost in 2030 from (IRENA, 2017) was around 450 €/kWh. Comparing VRFB to LTO in the same cycle basis in 2030, the VRFB capital cost in our optimistic future scenario is still slightly lower than the estimation of LTO from IRENA, 295 €/kWh to 310 €/kWh.

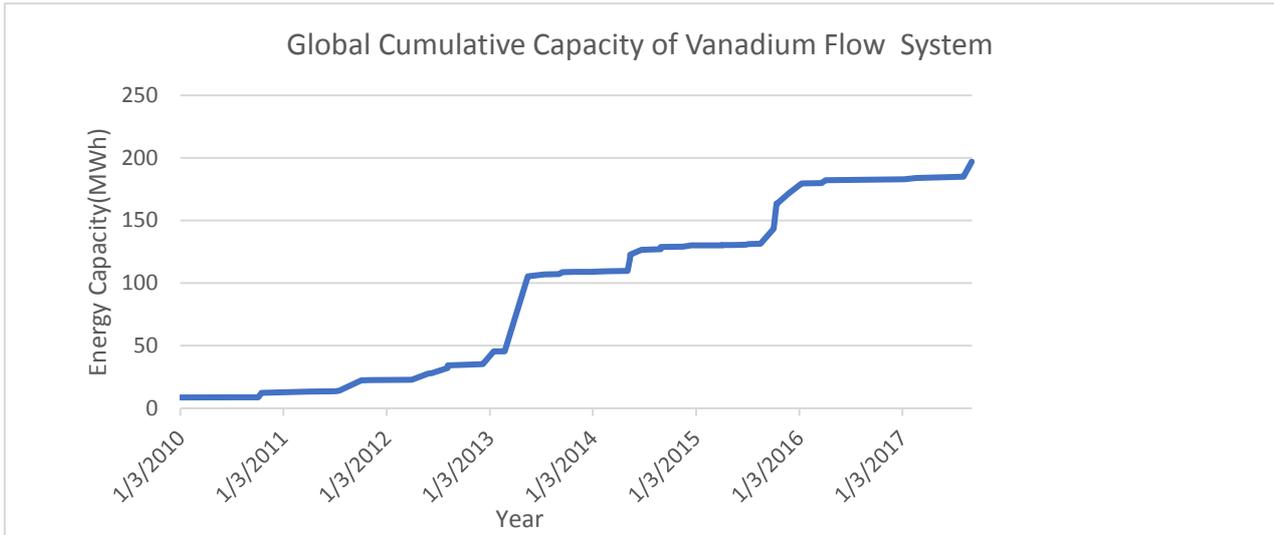


Figure 20 Global Cumulative Capacity from DOE (“DOE Global Energy Storage Database,” n.d.)

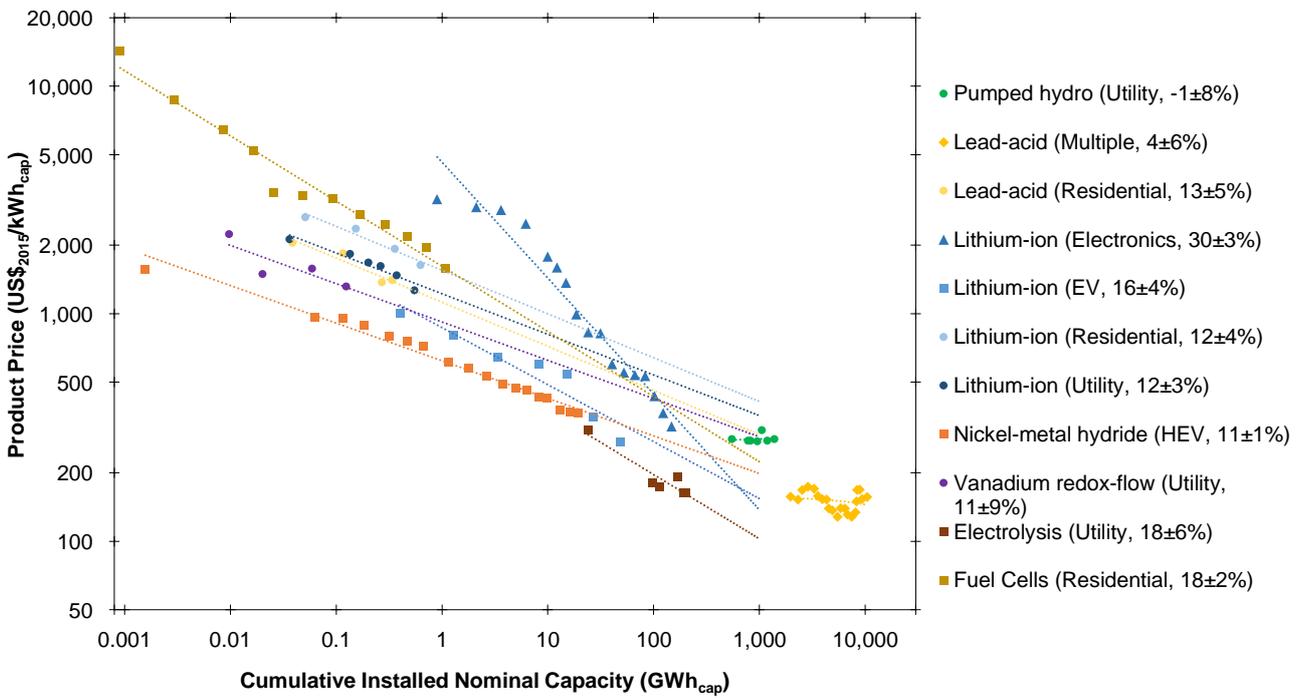


Figure 21 Cost projection of different energy storage technology (Schmidt et al., 2017)

## 8. Conclusion

In this study, we reviewed the background information of vanadium flow battery in terms of history, major benefits and limitations from previous researches, identified the components that the system consists of and probed into the economic perspective of VRFB which covered both system and the six main component's historical cost. With compiled present and future cost of the major components, we then constructed a bottom-up cost model for different-hour VRFB system and estimated their system capital costs in present, future conservative and future optimistic scenarios. The use of a bottom-up cost analysis is an explicit methodology of estimating VRFB's cost with a detailed inventory breakdown as well as identifying notable components to which overall system capital cost are most sensitive. Apart from understanding which VRFB configuration is more economically favourable under possible future events, the analysis also assisted in highlighting the cost and component share difference between scenarios. The study is followed by a statistical analysis, Monte Carlo Analysis which combined vanadium active species, ion-exchange membrane, electrode felt, bipolar plate, gasket and cell frame, these uncertain parameters to develop a probability distribution of probable cost of a representable 500kW 4-hour VRFB system in the future. We also demonstrated how mass production and leasing electrolyte enable the system capital cost to drop tremendously. With comparative assessment been done, our finding verified the plausible VRFB system cost stated in Schmidt et al.,(2017) and agreed with their study that VRFB has a strong potential to lead the market of stationary storage.

In spite of the fact that the studies showed the leading potential of VRFB in the market of stationary storage, persistent effort from various stakeholders is required to make it to a reality. For academics, apart from thorough electrochemical investigations on VRFB performance with cheaper and more efficient cell stack material to improve average voltage output, it is also crucial to conduct cost studies on the supplementary system in a VRFB system because our study showed that the power

components other than cell stacks such as control system and fluid regulation system added up to more than 50% of the power component's total cost in the future. Also, recent study revealed Nano-molecule might potentially increase tenfold the amount of energy in the electrolyte ("Researchers say new 'flow battery' could charge electric cars in seconds," 2018). This might raise academic interest in cutting off the demand of vanadium active species in favour of a step change. If nanotechnology could be applied in VRFB system. For industries and developers, in order to seek an abrupt change about VRFB capital cost, it is essential to explore the feasibility of the business model of electrolyte leasing because it can avoid the huge upfront project investment and spare risks. Also, communication with research and development academic group remained critically important to improve manufacturing processes and share their previous research achievements.

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