MARTIN HAJEK

ANALYSIS OF POTENTIAL APPLICATIONS AND BUSINESS MODELS FOR BATTERY ENERGY STORAGE SYSTEMS ON A LOW AND MEDIUM VOLTAGE DISTRIBUTION SYSTEMS IN BRAZIL

Dissertation presented at post-graduation program in electrical engineering program, area of concentration Energy Systems, Department of Electrical Engineering, Technology Sector, Federal University of Paraná, with partnership of Technische Hochschule Ingolstadt, as part of the activities to obtain the title of Master of Electrical Engineering.

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ABSTRACT

Resource scarcity, global warming and environmental disasters increased environmental awareness and unleashed remarkable worldwide transformation efforts away from fossil to renewable energy resources based generation during the last decade. There is a global trend for Electrical Energy Storage Systems (ESS) and especially batteries are one of the promising solutions for quality and safety in future, smart electricity networks with high shares of fluctuating renewable energy generation. Applicability and technical economic performance of distributed battery systems are strongly dependent on multiple issues, which include the project location, environment, electricity market regulations, application, technology, ownership and remuneration scheme. This way, knowledge and best practice for distributed battery utilization, developed in different environments, cannot be transferred directly to the national case, but local circumstances and needs have to be studied and appropriate, customized solutions identified. Aligned with the worldwide efforts on R&D to improve techno-economic performance of battery technologies, the latest public call for strategic R&D projects from the Brazilian Electricity Regulatory Agency – ANEEL, aims to identify reasonable applications and business models for distributed energy storage systems in Brazil. Objective of this work is to develop a method to identify how distributed battery systems can be used to improve the quality of renewable electricity networks on a nationalized level. To reach this, a literature research on the fundaments of battery technologies and applications, followed by a data collection on the state of the art in R&D for distributed battery systems are executed. The Brazilian electricity market is studied in terms of general structure, participation parties and relevant regulatory for distributed generation and storage application. An overview of all relevant data and the developed, detailed process, to identify appropriate business models for distributed battery application are presented. Based on the outcome of the last Public call for proposals from the strategic R&D project, known as *Chamada 21*, a roadmap for distributed storage systems in Brazil for the next four years is created, including a classification in six main classifications of battery types and applications. The functionality of the developed method is proved by identification of one exemplary project of distributed battery system utilization for each of the identified classifications from the Brazilian road map. Under current market and environment conditions, these projects are further simulated in terms of techno economic performance with the smart grid simulation program Homer Energy. The results of cost and performance are compared with conventional solutions, to identify the suitability of distributed battery systems and potential market niches. In terms of small scale, isolated off-grid electrifications there have been already advantageous overall operation cost identified. The method as well as the utilized simulation program turned out to be reasonable tools to identify business models for distributed battery applications in Brazil and calculate the expected costing structures.

Keywords: Battery Energy Storage. Business Case. Low Voltage. Medium Voltage. Brazil. Electricity Storage.

RESUMO

A escassez de recursos, o aquecimento global e os desastres naturais aumentaram a conscientização ambiental e desencadearam notáveis esforços de transformação em todo o mundo, afastando da geração baseada em fontes fósseis para a geração de recursos energéticos renováveis na última década. A tendência global de Sistemas de Armazenamento de Energia Elétrica, especialmente as baterias, é uma promissora solução para a qualidade e segurança dos futuros sistemas de redes elétricas inteligentes com uma elevada quota de produção de energia renovável. A aplicabilidade e o desempenho técnico e econômico dos sistemas de baterias distribuídas dependem fortemente de múltiplas questões, que incluem a localização do projeto, o ambiente, as regulamentações do mercado da eletricidade, a aplicação, a tecnologia, a propriedade e o regime de remuneração. Desta forma, o conhecimento e as melhores práticas para a utilização da bateria distribuída, desenvolvidos em diferentes ambientes, não podem ser aplicados diretamente no cenário nacional, mas as circunstâncias e necessidades locais precisam ser estudadas e soluções adequadas e customizadas identificadas. Alinhada com os esforços mundiais em P&D para melhorar o desempenho técnico-econômico das tecnologias de baterias, a última solicitação pública de projetos estratégicos de P&D da Agência Nacional de Energia Elétrica (ANEEL) tem como objetivo identificar aplicações razoáveis e modelos de negócios para sistemas distribuídos de armazenamento de energia no Brasil. O objetivo deste trabalho é desenvolver um método para identificar como os sistemas distribuídos de baterias podem ser usados para melhorar a qualidade das redes de eletricidade renovável a nível nacional. Para isso, foi realizada uma pesquisa bibliográfica sobre os fundamentos das tecnologias e aplicações de baterias, seguida de uma coleta de dados sobre o estado da arte em P&D para sistemas de baterias distribuídas. O mercado brasileiro de eletricidade é estudado em termos de estrutura geral, partindo da participação e regulamentação relevante para geração distribuída e aplicação de armazenamento. Apresenta-se uma visão geral de todos os dados relevantes e do processo desenvolvido e detalhado, para identificar modelos de negócios apropriados para aplicação de bateria distribuída. Com base no resultado do último convite à apresentação de propostas do projeto estratégico de pesquisa e desenvolvimento, denominado Chamada 21, é criado um modelo para sistemas de armazenamento distribuído no Brasil para os próximos quatro anos, incluindo uma classificação das seis principais classificações de tipos e aplicações de baterias. A funcionalidade do método desenvolvido é comprovada pela identificação de um projeto exemplo de utilização distribuída do sistema de bateria para cada uma das classificações identificadas a partir do modelo brasileiro. Sob condições atuais de mercado e meio ambiente, esses projetos são simulados em termos de desempenho técnico-econômico com o programa de simulação de redes elétricas inteligentes no Homer Energy. Os resultados de custo e desempenho são comparados com soluções convencionais, para identificar a adequação de sistemas de baterias distribuídas e potenciais nichos de mercado. Em termos de eletrificações isoladas de fora da rede, em pequena escala, já foram identificados custos de operação global vantajosos. O método e o programa de simulação utilizado revelaram-se ferramentas razoáveis para identificar modelos de negócios para aplicações de bateria distribuída no Brasil e calcular as estruturas de cálculo de custos esperadas.

Palavras-chave: Bateria, Modelo de Negócio, Baixa Tensão, Media Tensão, Brasil, Armazenamento de Energia Elétrica

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LIST OF EQUATIONS

Equation 1

$$Pb + HSO_4^- \underset{charge}{\overset{discharge}{\rightleftarrows}} PbSO_4 + H^+ + 2e^-$$

Equation 2

$$PbO_2 + 3H^+ + HSO_4^- + 2e^- \underset{charge}{\overset{discharge}{\rightleftarrows}} PbSO_4 + 2H_2O$$

Equation 3

$$Pb + PbO_2 + 2H_2SO_4 \underset{charge}{\overset{discharge}{\rightleftarrows}} 2PbSO_4 + 2H_2O$$

Equation 4

$$Li_{0,5}CoO_2 + 0{,}5Li^+ + 0{,}5e^- \underset{charge}{\overset{discharge}{\rightleftarrows}} LiCoO_2$$

Equation 5

$$C_6Li \underset{charge}{\overset{discharge}{\rightleftarrows}} 6C + Li^+ + e^-$$

Equation 6

$$Na \underset{charge}{\overset{discharge}{\rightleftarrows}} Na^+ + e^-$$

Equation 7

$$NiCl_2 + 2Na^+ + 2e^- \underset{charge}{\overset{discharge}{\rightleftarrows}} Ni + 2NaCl$$

Equation 8

$$FeCl_2 + 2Na^+ + 2e^- \underset{charge}{\overset{discharge}{\rightleftarrows}} Fe + 2NaCl$$

Equation 9

$$VO_2^+ + 2H^+ + e^- \underset{charge}{\overset{discharge}{\rightleftarrows}} VO^{2+} + H_2O$$

Equation 10

$$V^{2+} \underset{charge}{\overset{discharge}{\rightleftarrows}} V^{3+} + e^-$$

Equation 11

$$V^{2+} + VO_2^{+} + 2H^{+} \underset{charge}{\xleftarrow{\overrightarrow{discharge}}} V^{3+}VO^{2+} + H_2O$$

Equation 12

$$Zn + 4OH^{-} \underset{charge}{\xleftarrow{\overrightarrow{discharge}}} Zn(OH)_4{}^{2-} + 2e^{-}$$

Equation 13

$$O_2 + 2H_2O + 4e^{-} \underset{charge}{\xleftarrow{\overrightarrow{discharge}}} 4OH^{-}$$

Equation 14

$$2Zn + O_2 \underset{charge}{\xleftarrow{\overrightarrow{discharge}}} 2ZnO$$

LIST OF SYMBOS, APREVIATIONS AND TRANSLATIONS

Symbol / Word	Explanation / Translation
4OH-	hydroxide
A	Ampere
ACR	*Ambiente de Contratação Regulada* / The regulated market
ANEEL	Agência nacional de energia elétrica / Brazilian Electricity Regulatory Agency
APA	*Área de Proteção Ambiental* / Area of environmental protection
autoconsumo remote	remote auto consumes
C	carbon
CAPES	Coordenação de Aperfeiçoamento de Pessoal de Nível Superior / Coordination of Improvement of Higher Level Personnel (periodicals website)
CAPEX	Capital expenditures
CC	Charge controller
CCC	*Conta de Consumo de Combustíveis* / bill of fuel cost
CCEAL	*Contratos de Compra de Energia no Ambiente Livre* / Contracts for buying energy in free ambient
CCEAR	*Contratos de Comercialização de Energia do Ambiente Regulado* / contract of energy commercialization in regulated market
CCEAR DISP	*Contratos de Comercialização de Energia do Ambiente Regulado para Disponibilidade* / contract of energy commercialization in regulated market for capacity
CCEE	*Câmara de Comercialização de Energia Elétrica* / Electric Energy Trading Chamber
CCSD *Mensal*	monthly MCSD
CDE	*Conta de Desenvolvimento Energético* / Energy Development Account

CDS	contract for deferral scheme
CMO	*Custo Marginal de Operação* / marginal operation cost
COE	Lowest average cost per useful energy in [$/kWh]
COFINS	*Contribuição para Financiamento da Seguridade Social* / Federal taxes for contribution to social security
condomínio	condominium
CPP	critical-peak pricing
db	Data Base
Decomp	*Modelo de Planejamento da Operação de Sistemas Hidrotérmicos Interligados de Curto Prazo* / Planning Model for the Operation of Short-Term Interconnected Hydrothermal Systems
DG	Distributed Generation
DNI	Direct Normal Irradiance
DOE	Department of Energy
DPP	demand-pull policies
DR	demand response
DRP	Demand resource provider
DSM	demand side management
DSO	Distribution System Operators
E°	standard electrode potentials
EE	energy efficiency
EES	Electrical Energy Storage
EESS	electrical energy storage system
EEST	Electrical Energy Storage Technology
Encargo por Segurança Energética	Energy Security Charge
ES	Energy Storage
ESCO	energy serving companies
ESPC	Energy savings performance contracts
ESS	Energy Storage System
ESS1	*Encargos de Serviços de Sistema*

FeCl2	iron chloride
FR	Frequency regulation
geração compartilhada	shared generation
HV	High Voltage
IA	*Índice De Atendimento Rural* / Rural Attendance Index
ICMBio	*Instituto Chico Mendes de Conservação da Biodiversidade* / Institute Chico Mendes for Biodiversity
ICMS	*Imposto sobre circulação de mercadorias e serviços* / tax on the movement of goods and services
INV	Inverter
IRR	Internal rate of return
ISO	independent system operators
ISO-NE	ISO-New England
Isol.	isolated
kW	kilowatt
kWp	Kilowatt peak
Leilão	auction
LiCoO2	lithium cobalt oxide
LV	Low Voltage
MCSD	*Macanismo de Compensação de Sobras e Defícites* / mechanism of offset and deficit compensation
MCSE *Trocas Livres*	free exchange *MCSD*
MEC	*Ministério da Educação* / Brazilian ministry of education
MIGDI	*Microssistema Isolado de Geração e Distribuição de Energia Elétrica* / isolated micro distributed generation systems for electric energy
MISO	Midcontinent ISO
MRE	*Mecanismo de realocação de Energia* / energy relocation mechanism
MSCD Ex-post	an ex-post *MSCD* equilibration mechanism
MV	Medium Voltage

n.a.	Not available
n.c.	Not considered
n.r.	Not required
NAAlCl4	tetrachloroaluminate
Na-NiCl2	sodium-nickel-chloride
NaS	sodium sulfur
Newave	*Modelo de Planejamento da Operação de Sistemas Hidrotérmicos Interligados de Longo e Médio Prazo* / Planning Model for the Operation of Long- and Medium-Term Interconnected Hydrothermal Systems
NICL2	nickel chloride
NiCd	Nickel–Cadmium
NiMH	Nickel–Metal Hydride
NOR	Net Operating Revenue
NPV	Net Present Value
ONS	*Operador Nacional do Sistema Elétrico* / national operator of the electricity system
OPzS battery	*Ortsfeste Panzerplatten Batterie* / tubular plated lead acid battery
OPEX	operational expenditures
Parque Nacional Marinho	National marine park
PIS	*Programas de Integração Social* / Federal taxes for social integration
PLD	*Preço de liquidação das diferenças* / liquidation price of differences
PNS	Operador Nacional do Sistema Elétrico / National electricity system operator
PROINFA	*Programa de Incentivo às Fontes Alternativas de Energia Elétrica* / RE incentive program
PV	Photovoltaic
r&d	Research and Development
RE	renewable energy

SES	stationary energy storage
Reserva da Biosfera da Mata Atlântica	Biosphere Reserve of the Atlantic Forest
SIGFI	*Sistema Individual de Geração de Energia Elétrica com Fonte Intermitente* / individual generation system with intermittent source
T&D	Transmission and distribution
tarifa azul	blue tariff
tarifa branca	white tariff
tarifa verde	green tariff
THS	*Tarifa horo-sazonal* / time-of-use tariff model
ToU	time-of-use
TSO	Transmission System Operators
c.u.	consumer unit
V°	Standard cell voltage
VRF	Vanadium redox flow
ZEBRA	sodium/nickel chloridezinc
ZnBr	Zinc bromide
Zn	zinc
Zn(OH)2-4	Zincate

Source: The author

SUMMARY

1 INTRODUCTION

Global warming, shortage of fossil resources and nuclear catastrophes unleashed a worldwide change in the energy sector, away from fossil fuels and nuclear generation. In the electricity field great efforts are being made to advance in benefit from renewable energy resources. While mature, adjustable hydropower technology is already mostly captured due to its low cost and high reliability characteristics, fluctuating sources like wind and photovoltaic were growing rapidly during the last decade due to major development advances in efficiency improvements and economies of scale (REN21, 2016).

The Brazilian electricity system is traditionally based on large scale, centralized hydro power generation and therefore already dominated by renewable energy generation. Great, high voltage transmission lines are utilized to transport huge electricity amounts from the mostly remote areas of generation, over long distances, to the urban and industrial regions of consumption. Complex mathematic models and market mechanisms are applied to operate the national electricity system within quality and safety requirements. Economic development and growing population have led to steadily growing demand and expansion of hydro power installations over decades.

After the extreme drought in the beginning of the millennium turn, incentives and measures for thermal generation and climate prediction were taken. Also due to social-environmental restrictions for greater water resource utilization, additional programmes for generation portfolio diversification were introduced, (NERY, 2012). Continuing rising electricity demand during the last years let to increasing construction and operation of more costly thermoelectric plants and the introduction of tariff flags, which are adding an additional fee to the electricity tariff in relation to the usage of these generators, besides rising electricity prices, as ANEEL (2017a) website. To keep up with rising electricity demand without violating international decarbonisation agreements or social-environmental, increasing implementation of fluctuating photovoltaic and wind power generators and network expansions are expected.

1.1 CONTEXT

Under consideration of steadily reduction of fossil fired thermoelectric power plants and increasing operation of fluctuating renewable electricity generator the amount of controllable generation is shrinking continuously. This development leads to less network flexibility what can result in electricity quality problems from voltage irregularities until overproduction as well as shortages. Due to a changing environment, the traditional control energy instruments, applied by the system operators, might need further methods and possibilities to guarantee grid integrity, IEA-ETSAP IRENA (2015). Within the context of electricity system stability there is a set of starting points to influence the balance between generation and consumption as well as economic performance of the system as a total and for individual participants. These include activities on generation side (distributed generation), consumer side (demand response) or both (storage) (KÄRKKÄINEN, 2008). One of the most discussed solutions for renewable energy integration and energy quality improvement in the international field of research and development during the last years is based on batteries.

Batteries, being an electricity storage system and therefore capable to decouple the time of energy generation and consumption, are privileged for utilization in systems suffering from alternating time laps of electricity scarcity and abundance. There are hundreds of studies available on scientific online databases like Science Direct (2017), IEEE (2017) or Springer (2017), presenting different battery technologies and possible applications. Unfortunately, batteries show an extreme sensitivity of techno-economic performance depending on selected application, operation parameters, environmental and market conditions. Therefore, specific information about techno-economic performance of battery technologies, their most promising applications and potential benefits for the Brazilian electricity system is not available and has to be analysed.

1.2 OBJECTIVES

The main objective of this thesis is to support the development of environmental friendly electricity systems by implementation of battery energy storage systems.

Specific objectives of this thesis are:

- Identify the most promising battery technologies for energy distribution applications.
- Find out, for which energy distribution application batteries can be used.
- Review the state of the art in battery performance and utilization.
- Evaluate the electricity market regulations in terms of battery utilization in Brazil.
- Analyse the roadmap for battery applications in power systems in Brazil.
- Develop a method to select and combine all relevant data to create business models for distributed battery applications.
- Simulate technical-economic performance and business model of relevant battery technologies and applications on low and medium voltage distribution systems in Brazil with the simulation software Homer Energy.
- Validate and compare electricity costs for system operator in different use faces with and without utilization of battery energy storage system.

1.3 JUSTIFICATION

With the expansion of environmental friendly renewable energy resource in the global generation matrixes the impact of fluctuating power output and decreasing representation of controllable generation units on energy quality and security becomes a serious issue. Traditional electricity systems, which are constructed on the principle of demand driven, unidirectional power flow, from point of generation to point of consumption, are already facing major challenges in terms of technical as well as economical abilities. To guarantee system stability great efforts are taken by researches and politics to develop technical solutions and favouring regulatory frameworks to accompany the system transformation process.

At least since the latest public call for R&D proposals, *Chamada 21*, from the Brazilian Electricity Regulatory Agency (*ANEEL*), which is directed to concessionaires, permissionaires and authorized companies of the Brazilian electricity sector, the topic energy storage got great importance for Brazil. Information about the public call, *Chamada 21*, R&D focus is available under ANEEL (2016).

Over half a billion of R$ are going to be invested during the ongoing four years for investigation of distributed electricity storage technologies in Brazil.

Batteries, with their ability to decouple the moment of electricity generation and consumption in combination with their fast reacting, modular and rateable power values and capacity are one of the favoured solution within this changing environment. Leading countries in terms of renewable energy promotion like California in the USA (Self-Generation Incentive Program), compare CPUC (2017), or Germany (*KFW Erneuerbare Energien Speicher Kredit 270*), compare KFW (2016), are already applying regulatory changes to promote distributed battery utilizations in combination with renewable generators.

Basic justification of this thesis is to analyse how battery energy storage systems can contribute positively to low and medium voltage electricity systems in Brazil. Therefore, the technological and economic potential of battery systems and their possible applications under consideration of local market regulations and environmental conditions must be known. The complex environment of distributed battery storage applications needs to be structured and relevant parameters of influence must be connected to each other, to enable the creation of customized business models with improved technical and economic performance.

A method is developed, which connects important information from relevant areas and this way indicates technical possible business cases for different distributed battery applications and provides all required data to carry out calculations and simulations in terms of operation and economic feasibility. The developed method can be applied to analyse any intended distributed battery application, guiding the user on which areas to study and analyse and which information to collect.

1.4 MAJOR RESULTS

Generally distributed battery storage systems turned out to cope with the different operational requirements in the wide field of applications, to support the development of environmental friendly electricity systems. The major contributions of this study in consistent with the specific objectives are:

- The most promising battery technologies for energy distribution applications are lead acid, lithium ion, vanadium redox flow, sodium and metal air batteries.

- Batteries can be used for far over 20 different energy distribution applications.
- The function and main technical characteristics of five different battery technologies are shown, which show highest roundtrip efficiency rates for lithium-ion, simple capacity upgrade but great efficiency variations in terms of operation for VRF systems. High minimal state of charge and low cycle life for lead acid batteries and low maturity of the promising metal air battery technology.
- Electricity market regulations show chances for distributed battery applications especially in combination with distributed generation and rural electrification.
- The roadmap for battery applications in the Brazilian power system indicate projects in various combinations of capacity, power, voltage level, technology and for different objectives from isolated residential electrification until large scale voltage regulation on a medium voltage level.
- A method to select and combine all relevant data to create business models for distributed battery applications is developed and its functionality successfully shown on the example of six different battery application projects.
- The technical-economic performance of the six relevant battery applications on low and medium voltage distribution systems in Brazil are simulated with the smart grid simulation software Homer Energy.
- The outcomes of all simulations are validated an electricity costs for system operator are compared with alternative technologies for battery energy storage system application.

1.5 STRUCTURE OF DISSERTATION

The thesis is structured in six chapters. First chapter starts with an Introduction and shows the objectives and justifications for distributed battery applications in respect to the actual developments on renewable energy generation trends, and the latest efforts on national R&D for storage applications in Brazil. Further the structure of this work is explained. The second chapter gives an overview of the state of the art in battery technologies, existing application as referred to the energy storage projects database from the US Department of Energy (DOE) and an overview of the structure of the Brazilian electricity system and relevant market regulations for battery system operation. Chapter 3 includes a literature review on the state of the art on distributed battery technologies, their main applications and sensitive performance characteristics. Also, a review of potential business cases for distributed battery systems on low and medium voltage applications is accomplished. In chapter 4 all required materials, consulted in this thesis, are presented and the developed method, used to execute the techno-economic simulations of most promising technologies and applications for battery energy storage systems (ESSs), with the smart grid simulation software Homer Energy, is shown. The results of six simulations for different battery system operations under relevant applications and market conditions are shown in chapter 5. Thereby the developed method is applied stepwise from the identification of current situation to be improved until the techno economical evaluation. The last chapter, number 6, contains conclusions about the developed method, the roadmap for distributed battery storage applications in Brazil and suggestions for future works.

2 BATTERY ENERGY STORAGE SYSTEMS

Chapter two is structured in battery technology selection process and theoretical foundation of selected technologies. To identify the most relevant battery technologies, the open source DOE Global Energy Storage Database is analysed in terms of project quantity and storage capacity by technology type. The database is available online under Sandia National Laboratories (2016). Based on literature, the function, chemistry and technical characteristics of all selected battery types are explained in a second step.

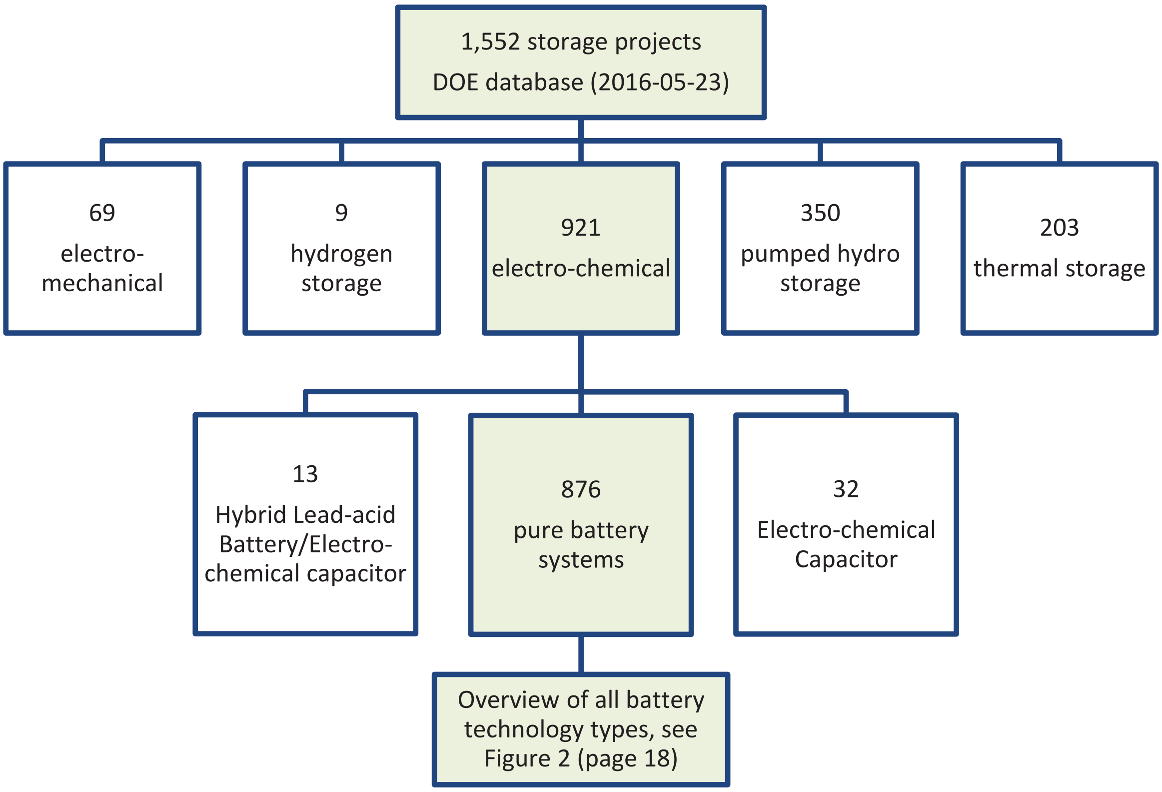
2.1 SELECTION PROCESS OF BATTERY TECHNOLOGIES

To identify the most relevant battery technologies which are considered for techno-economic cost and performance simulations as part of this thesis the open source DOE GLOBAL ENERGY STORAGE DATABASE is used as reference for global technology trends.

The database is operated by the Office of Electricity Delivery & Energy Reliability from Sandia National Laboratories in the USA. The database collects and provides information about global energy storage projects from the status of announcement until decommissioning. New datasets can be added online, see hyperlink at Sandia national laboratories (2016), by any person after creation of a user account.

The database lists, at the moment of download (2016-05-23), 1,552 storage projects, thereof 702 verified and 850 under verification. Out of the total, 921 projects are classified as electro-chemical energy storage technologies, 429 verified and 492 under verification and 876 are pure battery systems. The structure of DOE database by ES technology type is given in FIGURE 1.

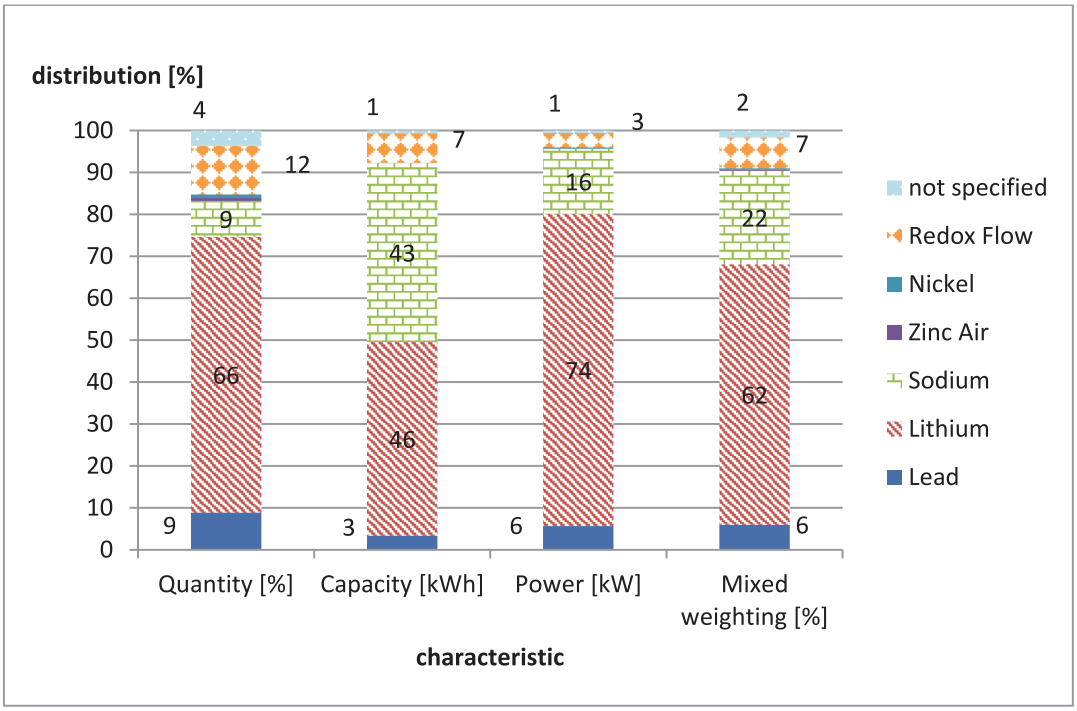
FIGURE 1: STRUCTURE OF DOE ES DATABASE



SOURCE: Adapted from SANDIA NATIONAL LABORATORIES (2016)

An overview of battery type distribution in terms of quantity, power and capacity based on the total dataset of battery projects is given in FIGURE 2. The criterion "mixed weighting" represents the average percentage of all three criteria considering an equal significance.

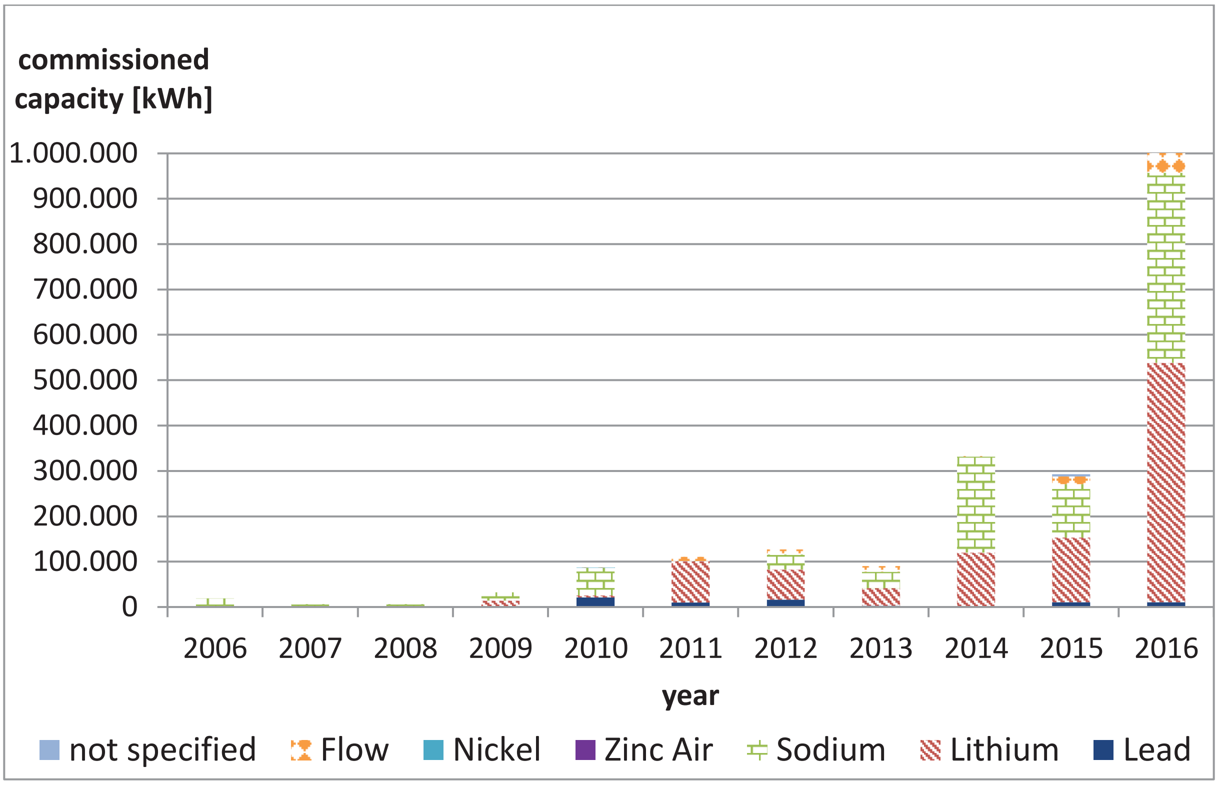
FIGURE 2 - DOE DATABASE BATTERY TYPE DISTRIBUTION



SOURCE: Adapted from Sandia National Laboratories (2016)

As illustrated in FIGURE 2, lithium-ion based batteries show by far the biggest fraction, followed by Sodium, Flow and Lead batteries. About two percent of the projects do not include specification of utilized battery type and Zinc-Air and Nickel based batteries do only represent about one percent of the total. Since about nine percent of all datasets provide information about nominative power only but not about duration at rated power the nominal capacity cannot be calculated and therefore the presented values for capacity split may differ from reality. To see the technology trend FIGURE 3 screens the commissioned battery project capacities in kWh of the last ten years split by battery type. Only data sets containing a commission date are considered taking the assumption that these are the systems which where, are or going to be operational indeed.

FIGURE 3: YEARLY COMMISSIONED BATTERY CAPACITY BY TYPE



SOURCE: Adapted from Sandia national laboratories (2016)

First, a remarkable growth in terms of general installed capacity is notable, from less than 20 MWh in 2006 to over one GWh in 2016. Second the domination of lithium and sodium batteries between 2012 and 2016, representing about 90 % of overall commissioned battery systems.

An overview of all battery projects structured by all battery type and including information about absolute and relative installed quantity, power and capacity, is given in TABLE 1.

TABLE 1: OVERVIEW OF ALL BATTERY PROJECTS FROM DOE DATABASE

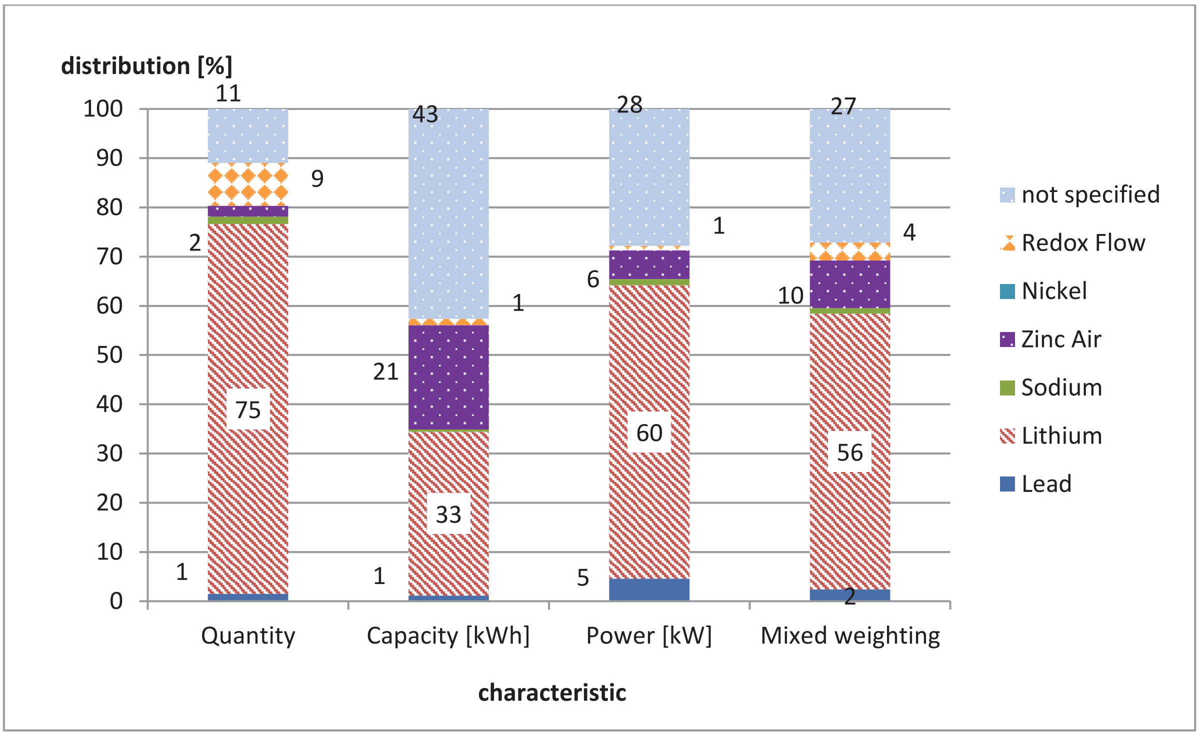
Battery Type	**Quantity**		**Capacity**		**Power**	
	units	**%**	**kWh**	**%**	**kW**	**%**
Advanced Lead-acid Battery	23	3	25,487	1	40,800	23
Electro-chemical	32	4	15,500	1	6,250	32
Flow Battery	3	0	60	0	10	3
Hydrogen Bromine Flow Battery	1	0	0	0	0	1
Iron-chromium flow Battery	1	0	1,000	0	250	1
Lead Carbon Battery	5	1	250	0	500	5
Lead-acid Battery	38	4	19,084	1	10,464	38
Lithium Ion Titanate Battery	19	2	54,961	3	12,695	19
Lithium Iron Phosphate Battery	120	14	198,173	9	152,500	120
Lithium Manganese Oxide Battery	2	0	1,100	0	1,100	2
Lithium Nickel Cobalt Aluminum Battery	3	0	3,560	0	2,600	3
Lithium Nickel Manganese Cobalt Battery	12	1	21,620	1	36,255	12
Lithium Polymer Battery	20	2	9,852	0	7,458	20
Lithium-ion Battery	399	46	714,815	33	594,557	399
Lithium-titanate	1	0	0	0	0	1
Metal Air Battery	0	0	0	0	0	0
Nickel based Battery	0	0	0	0	0	0
Nickel Iron Battery	3	0	0	0	0	3
Nickel Metal Hydride Battery	1	0	0	0	0	1
Nickel-cadmium Battery	3	0	250	0	3,000	3
Sodium based Battery	1	0	600	0	100	1
Sodium-ion Battery	10	1	4,108	0	825	10
Sodium-nickel-chloride Battery	30	3	29,651	1	10,885	30
Sodium-sulfur Battery	34	4	893,400	41	156,500	34
Valve regulated Lead-acid Battery	12	1	28,669	1	10,114	12
Vanadium Redox Flow Battery	58	7	132,912	6	31,985	58
Zinc Air Battery	6	1	0	0	0	6
Zinc Bromine Flow Battery	31	4	12,124	1	3,095	31
Zinc Iron Flow Battery	6	1	6,480	0	2,256	6
Zinc Manganese Dioxide Battery	1	0	0	0	0	1
Zinc-nickel Oxide Flow Battery	1	0	200	0	100	1
Sum	**876**	**100**	**2,173,857**	**100**	**1,084,299**	**876**
Grouped by type and material as shown in FIGURE 2:	**units**	**%**	**kWh**	**%**	**kW**	**%**
Lead	78	9	73,491	3	61,878	78
Lithium	576	66	1,004,082	46	807,165	576
Sodium	75	9	927,759	43	168,310	75
Zinc Air	6	1	0	0	0	6
Nickel	7	1	250	0	3,000	7
Flow	102	12	152,776	7	37,696	102
not specified	32	4	15,500	1	6,250	32

SOURCE: Adapted from Sandia National Laboratories (2016)

Further interesting information which can be read in TABLE 1 is that the average installed capacity of sodium based projects is about seven times higher than for lithium-ion based battery projects. Or with different words there is a tendency of lithium batteries for smaller projects in terms of storage capacity.

To identify current technology trends all announced projects are observed separately, as represented in FIGURE 4.

FIGURE 4 - ANNOUNCED PROJECTS BATTERY TYPE CONTRIBUTION



SOURCE: Adapted from Sandia National Laboratories (2016)

As shown in FIGURE 4, three out of four announced battery projects are planned to be realized with lithium-ion batteries, representing 33 % of total capacity and 60 % of total installed power. Quantity of flow batteries shrinks by one third compared to the overall database to about eight percent and only represents one percent of the total announced capacity. This shows that the characteristic of capacity up scalability by constant installed power of flow batteries seems not to be used by future projects in direct comparison to the total projects. Nearly eleven percent of the projects do not announce the specific battery technology but represent close to 43 % of the total announced capacity. There are only three percent of projects planned to work with zinc batteries, but the scheduled capacity will represent over 21 % of the total. The full list of announced battery projects with information about quantity, nominal capacity and power is given by TABLE 2.

TABLE 2: ANNOUNCED BATTERY PROJECTS FROM DOE DATABASE

Battery Type	**Quantity**		**Capacity**		**Power**	
	units	**%**	**kWh**	**%**	**kW**	**%**
Advanced Lead-acid Battery	0	0	0	0	0	0
Electro-chemical	15	11	458,504	43	130,313	28
Flow Battery	1	1	1,440	0	450	0
Lead-acid Battery	0	0	0	0	0	0
Lithium Ion Titanate Battery	0	0	0	0	0	0
Lithium Iron Phosphate Battery	1	1	20,000	2	10,000	2
Lithium-ion Battery	101	74	337,690	31	268,737	57
Metal Air Battery	0	0	0	0	0	0
Sodium based Battery	0	0	0	0	0	0
Sodium-ion Battery	0	0	0	0	0	0
Sodium-Sulfur Battery	0	0	0	0	0	0
Valve regulated Lead-acid Battery	0	0	0	0	0	0
Vanadium Redox Flow Battery	9	7	10,265	1	2,665	1
Zinc Air Battery	3	2	228,008	21	27,250	6
Zinc Bromine Flow Battery	0	0	0	0	0	0
Hydrogen Bromine Flow Battery	0	0	0	0	0	0
Iron-chromium flow Battery	0	0	0	0	0	0
Lead Carbon Battery	2	1	12,500	1	21,500	5
Lithium Manganese Oxide Battery	0	0	0	0	0	0
Lithium Nickel Cobalt Aluminium Battery	0	0	0	0	0	0
Lithium Nickel Manganese Cobalt Battery	0	0	0	0	0	0
Lithium Polymer Battery	0	0	0	0	0	0
Lithium-titanate	1	1	250	0	375	0
Nickel Iron Battery	0	0	0	0	0	0
Nickel Metal Hydride Battery	0	0	0	0	0	0
Nickel-cadmium Battery	0	0	0	0	0	0
Sodium-nickel-chloride Battery	2	1	5,000	0	6,000	1
Zinc Iron Flow Battery	1	1	2,000	0	1,000	0
Zinc Manganese Dioxide Battery	1	1	0	0	100	0
Zinc-nickel Oxide Flow Battery	0	0	0	0	0	0
Sum	137		1,075,657		468,390	
Grouped by type and material:	**units**	**%**	**kWh**	**%**	**kW**	**%**
Lead	2	1	12,500	1	21,500	5
Lithium-ion	103	75	357,940	33	279,112	60
Sodium	2	1	5,000	0	6,000	1
Zinc Air	4	3	228,008	21	27,350	6
Nickel	0	0	0	0	0	0
Flow	11	8	13,705	1	4,115	1
not specified	15	11	458,504	43	130,313	28

SOURCE: Adapted from Sandia National Laboratories (2016)

Based on the total and announced technology representation, see TABLE 1 and TABLE 2, and under consideration of the evolution of yearly commissioned battery capacities, compare FIGURE 3, the most relevant battery types are summarized in TABLE 3.

TABLE 3: SUMMARY OF BATTERY TECHNOLOGIES BY RELEVANCE

total	**Quantity [%]**	**Capacity [%]**	**Announced**	**Quantity [%]**	**Capacity [%]**
Lithium-ion	66	46	**Lithium-ion**	75	33
Flow	12	43	**Flow**	9	1
Sodium	9	7	**Zinc Air**	2	21
Lead	9	3	**Lead**	1	1

SOURCE: Adapted from Sandia National Laboratories (2016)

2.2 FUNDAMENTALS OF SELECTED BATTERY TECHNOLOGIES

The function and fundamental chemical reactions, structure, materials and theoretical technical parameters of the selected battery types are represented in this chapter. The considered technical parameters are nominal cell voltage, round trip efficiency, self-discharge rate, order of energy and power density, minimum state of charge, float lifetime and cycle time in relation of discharge depth, (dis-)charge rates – so called C-rate. All information represented in this chapter are based on the publications Garche (2009), Moseley and Garche (2015) and Becker et al. (2015).

2.2.1 Lead Acid Batteries

The first rechargeable Lead Acid Battery was already presented in 1859 by the French physicist Gaston Planté and lead batteries can today be considered as a matured technology. The battery cell contains of an electrode pair in form of flat lead (Pb) plates being one captured with lead oxide (PbO_2) as positive active-material Garche (2009). A solution of water and sulfuric acid, aqueous sulfuric acid (H_2SO_4), serves as electrolyte.

Equations of electrochemical reactions during (dis-)charging process as published by Garche (2009) are shown in Equation 1, Equation 2 and Equation 3:

Negative electrode reaction:

$$Pb + HSO_4^- \underset{charge}{\overset{discharge}{\rightleftarrows}} PbSO_4 + H^+ + 2e^-$$ EQUATION 1

Positive electrode reaction:

$$PbO_2 + 3H^+ + HSO_4^- + 2e^- \underset{charge}{\overset{discharge}{\rightleftarrows}} PbSO_4 + 2H_2O$$ Equation 2

Overall reaction:

$$Pb + PbO_2 + 2H_2SO_4 \underset{charge}{\overset{discharge}{\rightleftarrows}} 2PbSO_4 + 2H_2O$$ EQUATION 3

Standard cell voltage $V°$ is the difference of the standard electrode potentials $E°$ from both reactions at positive electrode $(+1.690\,V)$ and negative electrode $(-0.358\,V)$ with a maximum of $V^{\circ} = 2.048\,V$ for aqueous electrolyte solutions. This is also the maximum value for aqueous commercial battery systems, Reiner Korthauer et al. (2013) and Garche (2009).

As shown in Equation 1 during discharging process the Pb of the negative electrode reacts with the HSO_4^- ions from the electrolyte, creating H^+ ions, non-conductive lead(II) sulfate $PbSO_4$ and two electrons e^-. The electrons lead to negative charge of the therefore negative electrode, whereby the H^+ ions migrate to the positive electrode. At the positive electrode the Pb of the PbO_2 also reacts with HSO_4^- from the electrolyte to lead(II) sulfate $PbSO_4$, and the excess O_2 forms water with the H^+ ions, compare Equation 2. The reactions between Pb and HSO_4^- is equal at both electrodes, continuously weakening the electrolyte. Ones the positive and negative electrodes get connected via an electric circuit to feed a load, electrons from the negative electrode plate can flow through the circuit until the positive electrode, compensating the difference of electric charge.

The battery block is an assemblage of numerous cells connected to each other in line or parallel, depending on the desired resulting voltage, current and capacity characteristics, Pavlov (2011).

An overview of typical values for technical characteristics of lead-acid batteries based on Garche (2009) and Moseley and Garche (2015) is given in TABLE 4.

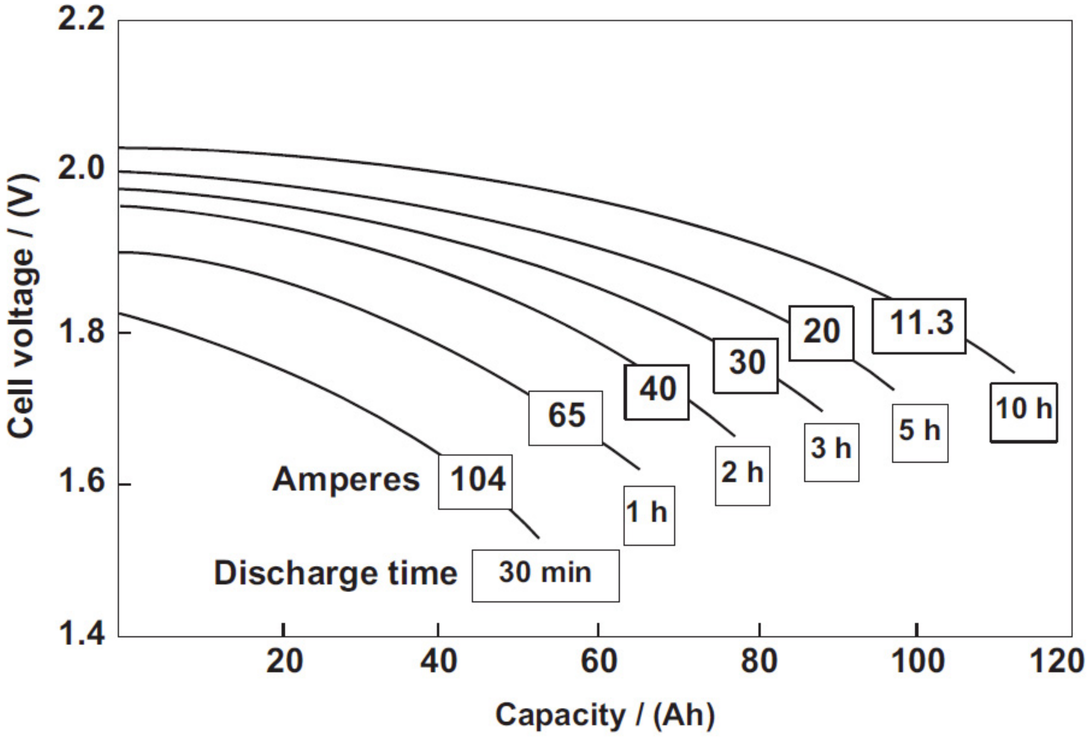
TABLE 4: TYPICAL VALUES FOR LEAD-ACID BATTERY CHARACTERISTICS

Battery Cell Characteristics	
Nominal cell voltage (V)	2.048 V
Round Trip Efficiency cell and system (%)	80-90 % cell / 70-80 % system
Self-Discharge rate (% per month at 20 °C)	1~12 %
Specific energy density for stationary batteries	25-40 Wh/kg; 40-100 Wh/dm³
Specific energy density on cell base	50-100 Wh/dm³
Specific power density for stationary batteries	100-500 W/kg; 400-600 W/dm³
Specific power density on cell base	10-100 W/dm³
Minimum State of Charge (%)	30 %
Nominal power until state of charge (%)	50 %
Discharge capacity characteristics	Compare FIGURE 5
Float life (yr)	5-15 years
Cycle-life dependent on discharge depth	Compare FIGURE 6

SOURCE: MOSELEY (2015), GARCHE (2009), BECKER ET AL. (2015)

The capacity of lead-acid batteries is strongly dependent on the utilized discharging time, whereby faster discharging cycles are realized by increasing currents, what leads to decreasing efficiency and therefore lower available energy capacities. An example of typical discharge efficiencies for lead-acid batteries in relation to discharge current and time is illustrated by FIGURE 5, Garche (2009).

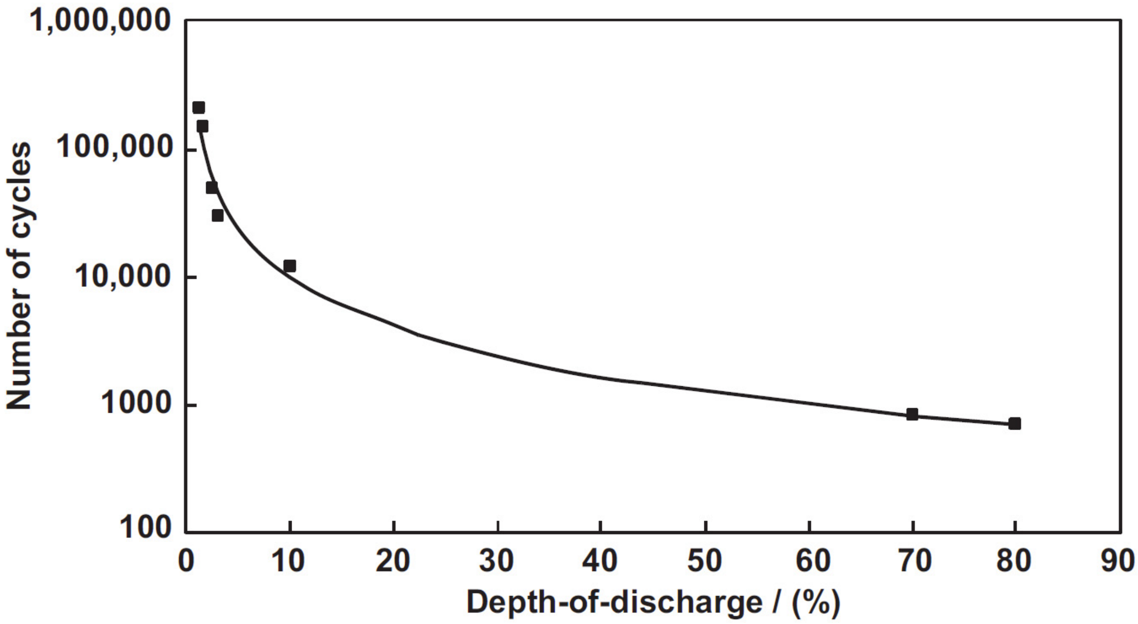
FIGURE 5: TYPICAL DISCHARGE CURVES FOR LEAD-ACID BATTERIES



SOURCE: GARCHE (2009)

The cycle-life represents the overall available discharge capacity of the battery until it fails and is calculated by total energy throughput divided by the nominal capacity of a single cycle. Cycle-life decreases with increasing depth of discharge, what might lead to divergences between theoretical required capacities as defined by the load and installed capacities as defined by efficiency or cost optimizations. A typical curve for variation of cycle-life, based on discharge depth is shown in FIGURE 6, as published by Garche (2009).

FIGURE 6: VARIATION OF CYCLE-LIFE WITH DOD OF A SPIRAL-WOUND VALVE-REGULATED LEAD-ACID BATTERY



SOURCE: GARCHE (2009)

At a depth-of-discharge in the range of 10 % in this exemplary curve operation of about 10,000 cycles could be realized, what represents a total energy throughput, until battery cell fails, equal to 1,000 times the battery capacity.

Investment costs are given by Sterner; Stadler (2014) with 90 – 355 €/kWh or 200- 490 €/kW respectively. Operation costs are given in with 0.16 – 0.76 €/kWh delivered by the storage device.

Beside the traditional, simple structure, there are further developed types of lead acid batteries available. These improvements are based in material addition or change of shape depending on intended performance improvements. One is the so called UltraBattery, a combination of conventional lead acid battery and ultracapacitor technology. Another common lead acid battery type is the OPzS battery *(Ortsfeste Panzerplatten Batterie)*, a long life flooded tubular plate battery. Last one is characterized by advantageous performances for deep cycling, lower maintenance and longer lifetime expectations compared to the traditional format. Since these advanced lead acid battery variations are based on the same principle, they are not explained in detail separately in this work.

2.2.2 Lithium-Ion Batteries

The first li-ion battery was developed in 1990 by Sony Energytec after lithium batteries have been taken off the market due to security problems as Moseley and Garche (2015). In general lithium-ion battery cells consist of two electrodes, a separator, electrolyte and a casing. The positive electrode, cathode during discharge process, consists of a thin copper foil which serves as current collector, coated with positive electrode material. The negative electrode, anode during discharge process, is made of a thin aluminium foil, coated with negative electrode material. A separator prevents electric contact between the electrodes but is permeable for lithium ions. An ion conductive electrolyte which enables li-Ions to drift through the separator between anode and cathode during operation is a mixture of conducting salt and aprotic solvents - optional partly in combination with polymers. The casing prevents from material flow or unintended interaction between environment and cell chemistry. The electrode materials consist of active material particles, additives and a binder. Lithium compounds serve as active materials at both electrodes, whereby the most common combination uses carbon lithium intercalation compounds at the negative and lithium metal oxide at the positive electrode (MOSELEY; GARCHE, 2015).

The chemical reaction of a lithium-ion cell is described by Equation 4 and Equation 5, as published by Garche (2009), under consideration of Lithium cobalt oxide ($LiCoO_2$) at the positive and carbon C at the negative electrode, which represents the first lithium-ion battery produced by Sony in 1991 as Zackrisson et al. (2010).

Positive electrode reaction:

$$Li_{0,5}CoO_2 + 0{,}5Li^+ + 0{,}5e^- \underset{charge}{\overset{discharge}{\rightleftarrows}} LiCoO_2 \qquad \text{EQUATION 4}$$

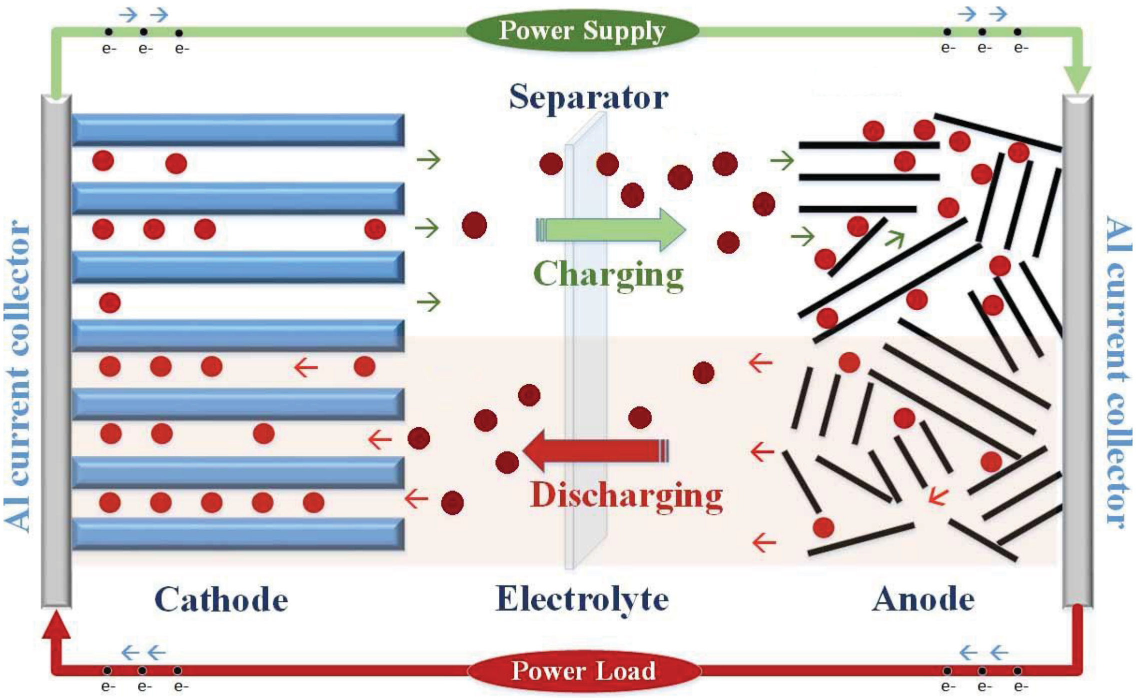
Negative electrode reaction:

$$C_6Li \; \underset{charge}{\overset{\overrightarrow{discharge}}{\longleftarrow}} 6C + Li^+ + e^-$$

EQUATION 5

During the discharge process electrons flow from the negative electrode (anode) through the load to the cathode. In the same time the lithium-ions, which are intercalated in the carbon of the anode, floats through the microporous separator membrane to the cathode, where they react with the Lithium cobalt oxide. During charging the process gets reversed due to electrode flow into the negative anode as Korthauer (2013). The charging and discharging process of lithium-ion battery cells is illustrated in FIGURE 7.

FIGURE 7: BASIC DESIGN OF A LITHIUM-ION CELL



SOURCE: BASED ON ‘PURDUE ENGINEERING’ (2016)

It is considerable that there are numerous types of lithium-ion batteries working with different material combinations and therefore being characterized by a wide range of technical performance. A typical value of nominal cell voltage for commercial lithium-ion cells is $3.7\,V$, reaching cutoff voltage at fully discharge with $2.7\,V$ as Moseley and Garche (2015). A summary of typical values for lithium-ion batteries is given in TABLE 5.

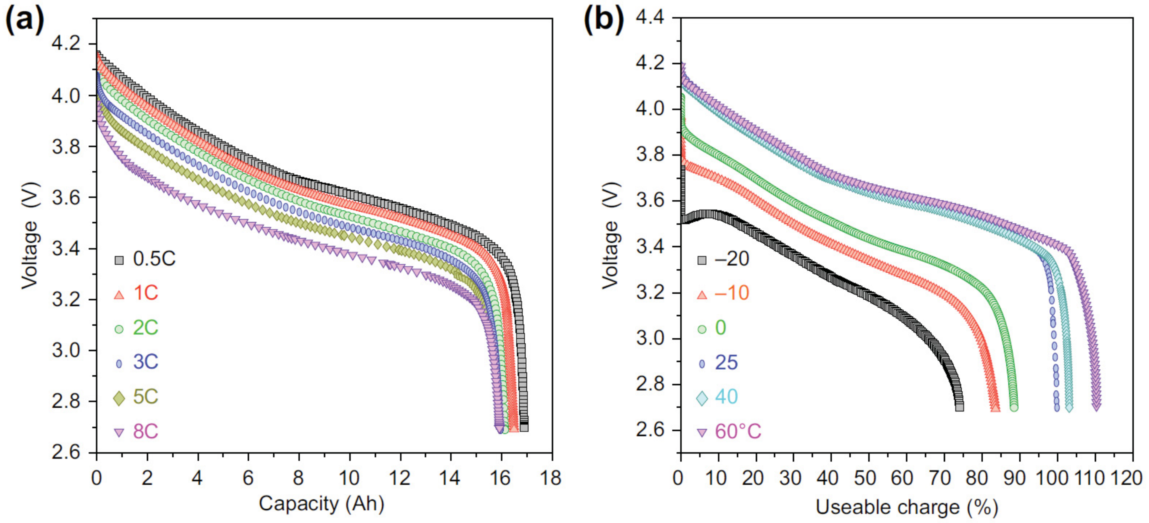
TABLE 5: TYPICAL VALUES FOR LITHIUM-ION BATTERY CHARACTERISTICS

Battery Cell Characteristics	
Nominal cell voltage (V)	3.0-4.2 V
Round Trip Efficiency cell and system (%)	95-99 % cell / 80-90 % system
Self-Discharge rate (% per month at 20 °C)	~2-10 %
Specific energy density on cell level	90-240 Wh/kg, 200-500 Wh/dm³
Specific power density	up to 1500 W/kg
Minimum State of Charge (%)	0 %
Nominal power until state of charge (%)	20 %
Max. Charge Rate (A/Ah)	40 C (1C=1A/1h)
Discharge capacity characteristics	Compare FIGURE 8
Float life (yr)	5-20 years
Cycle-life dependent on discharge depth	n.a.

SOURCE: MOSELEY (2015), BECKER ET AL. (2015)

An example for discharge capacity characteristics of lithium-ion battery cell in dependence of a variation of applied C-rates and under different temperatures is given in FIGURE 8, as published by Moseley and Garche (2015).

FIGURE 8: (A) DISCHARGE CHARACTERISTICS OF A KOKAM 17-AH/3.7-V LITHIUM-ION BATTERY AT DIFFERENT C-RATES AND ROOM TEMPERATURE. (B) DISCHARGE CHARACTERISTICS AT 0.5C AT DIFFERENT TEMPERATURES.



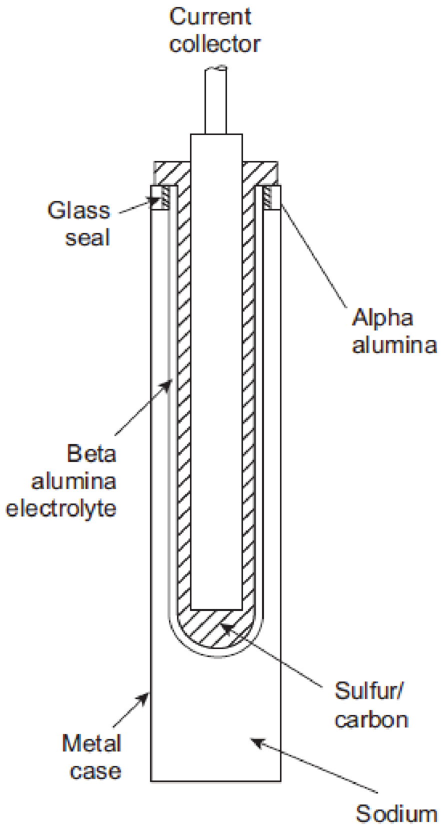
SOURCE: MOSELEY (2015)

Investment costs are given by Sterner; Stadler (2014) with 170 – 600 €/kWh or 170 – 600 €/kW respectively. Operation costs are given in with 0.13 – 0.76 €/kWh delivered by the storage device.

2.2.3 Sodium Batteries

In general, there are two types of high temperature sodium batteries. Both use liquid sodium as active material of the negative electrode and a beta alumina ceramic component works as separator and electrolyte. Opposite to other battery technologies the electrodes are liquid, and the electrolyte is solid. Sodium sulfur batteries use sulfur at the positive electrode and work at a temperature range of around 300-350 °C. A schematic representation is given with FIGURE 9 as published by Moseley and Garche (2015).

FIGURE 9: SODIUM SULFUR CELL WITH CENTRAL SULFUR CONFIGURATION



Source: MOSELEY, GARCHE (2015)

Sodium-metal-halide batteries use molten sodium tetra chloroaluminate $(\mathrm{NaAlCl_4})$ as a secondary electrolyte in the section of the positive electrode. As positive active material an insoluble transition metal chloride is used, made of either iron chloride $(\mathrm{FeCl_2})$, nickel chloride $(\mathrm{NiCl_2})$ or a mixture of both. Since sodium-metal-halide batteries show various advantageous performance characteristics in comparison to sodium sulfur batteries, further data will only focus on sodium-metal-halide batteries (MOSELEY, 2015)

During discharge the sodium atoms of the negative electrode give an electron to the external circuit and the Na^+ floats through the beta alumina wall, compare Equation 6, and react with transition metal chloride of the positive electrode to sodium chloride and free transition metal, see Equation 7. At the positive electrode The standard cell voltage is constant at $V^\circ = 2.58\,V$ for positive electrodes working with pure sodium-nickel-chloride ($Na - NiCl_2$).If a mixture of nickel-chloride ($NiCl_2$) and iron(II)-chloride ($FeCl_2$) is used, the voltage drops down to $V^\circ = 2.35\,V$ after total discharge of nickel or during high power discharge to allow the iron chloride discharge reaction, as represented by Equation 8 (MOSELEY, 2015)

Negative electrode reaction:

$$Na \;\underset{charge}{\overset{discharge}{\rightleftarrows}}\; Na^+ + e^-$$

EQUATION 6

Positive electrode reactions:

$$NiCl_2 + 2Na^+ + 2e^- \;\underset{charge}{\overset{discharge}{\rightleftarrows}}\; Ni + 2NaCl$$

EQUATION 7

$$FeCl_2 + 2Na^+ + 2e^- \;\underset{charge}{\overset{discharge}{\rightleftarrows}}\; Fe + 2NaCl$$

EQUATION 8

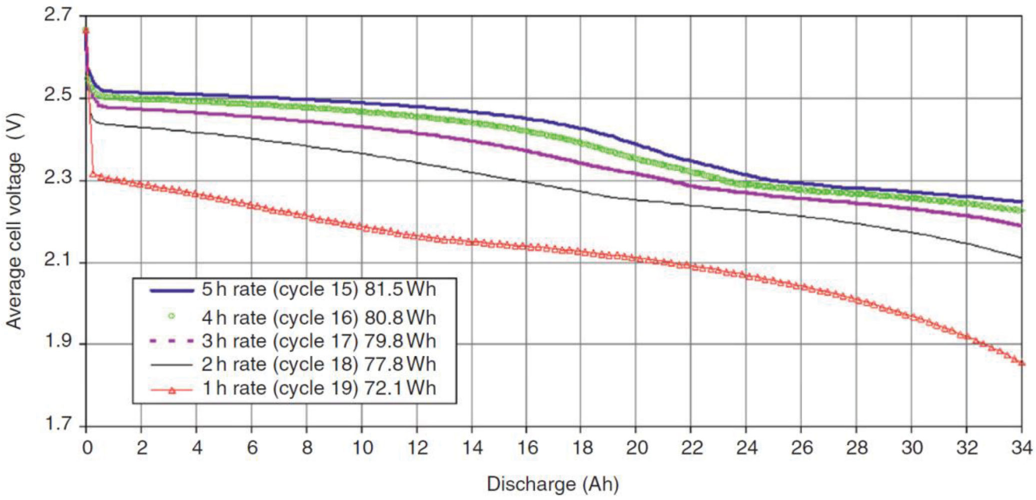
TABLE 6: TYPICAL VALUES FOR SODIUM-METAL-HALIL BATTERY CHARACTERISTICS

Battery Cell Characteristics	
Nominal cell voltage (V)	2.58 / 2.35 V
Round Trip Efficiency cell and system (%)	100 % cell 75-90 % (therm. losses, discharge rate) syst.
Self-Discharge rate (% per day)	Up to 5% per day due to thermal losses
Specific energy density on cell level	90-120 Wh/kg; 140-170 Wh/dm³
Specific power density	150-250 W/kg; 250-300 W/dm³
Minimum State of Charge (%)	~0 %
Nominal power until state of charge (%)	~0 % (pulse)
Max. Charge Rate (A/Ah)	Min charge time is 5h, ~0,5 C
Max. Charge Current (A)	15 A for 32-Ah cell (~0,5 C)
Discharge capacity characteristics	Compare FIGURE 10
Float life (yr)	15 years
Cycle-life dependent on discharge depth	4500 at 80 % dod

SOURCE: MOSELEY (2015), REINER KORTHAUER ET AL. (2013)

A typical discharge curve of a sodium-metal-halide cell is represented by FIGURE 10. MOSELEY (2015)

FIGURE 10: FAMILY OF DISCHARGE CURVES AND THE ACHIEVED ENERGIES SODIUM-NICKEL CHLORIDE CELL



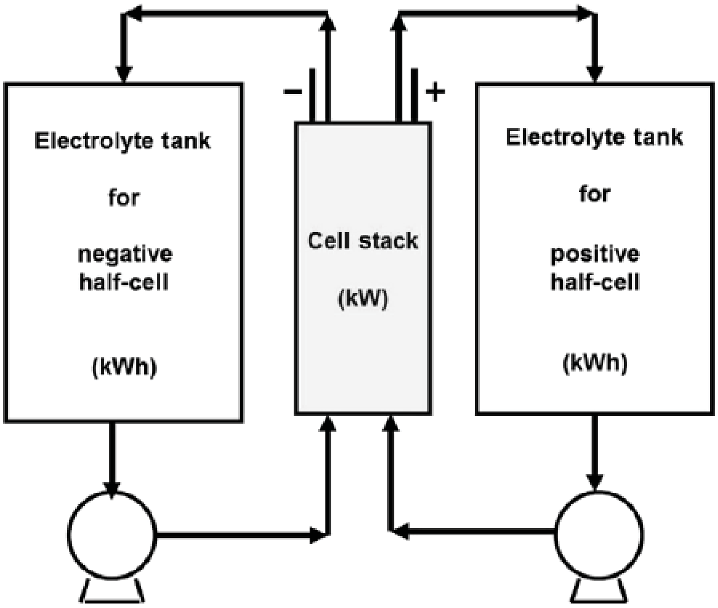
SOURCE: GARCHE (2009)

Investment costs are given by Sterner and Stadler (2014) with 265 – 645 €/kWh or 285- 1075 €/kW respectively. Operation costs are given in with 0.07 – 0.76 €/kWh delivered by the storage device.

2.2.4 Vanadium-Redox-Flow batteries

Redox-flow batteries use the potential difference of two electrolyte solution, stored in separated reservoirs separated by an ion-exchange membrane, as shown in FIGURE 11.

FIGURE 11: FLOW BATTERY SCHEMATIC REPRESENTATION



Source: MOSELEY, GARCHE (2015)

Vanadium-redox-flow battery is the commercially most developed flow cell chemistry and utilizes vanadium in their four oxidation states for both electrolytes, V(II)-(III) in the positive and V(IV)-(V) in the negative half-cells, MOSELEY (2015), GARCHE (2009). During discharge the pumped electrolytes pass the membrane on both sides, whereby the V(II) oxidises to V(III) and gives an electron to the negative electrode, compare Equation 9. The electron flows through the load to the positive current collector, where the V(V) gets reduced to V(IV), forming water as a by-product, as shown in Equation 10. The overall chemical reaction for charge and discharge is shown in Equation 11, as published by Garche (2009).

Negative electrode reaction:

$$V^{2+} \overset{\longrightarrow}{\underset{charge}{\xleftarrow{discharge}}} V^{3+} + e^{-}$$

EQUATION 9

Positive electrode reaction:

$$VO_2^+ + 2H^+ + e^- \overset{\longrightarrow}{\underset{charge}{\xleftarrow{discharge}}} VO^{2+} + H_2O$$

EQUATION 10

Overall reaction:

$$V^{2+} + VO_2^+ + 2H^+ \overset{\longrightarrow}{\underset{charge}{\xleftarrow{discharge}}} V^{3+} VO^{2+} + H_2O$$

EQUATION 11

Typical values for vanadium-redox-flow batteries are summarized in TABLE 7, based on Garche (2009), Moseley and Garche (2015) and Becker et al. (2015).

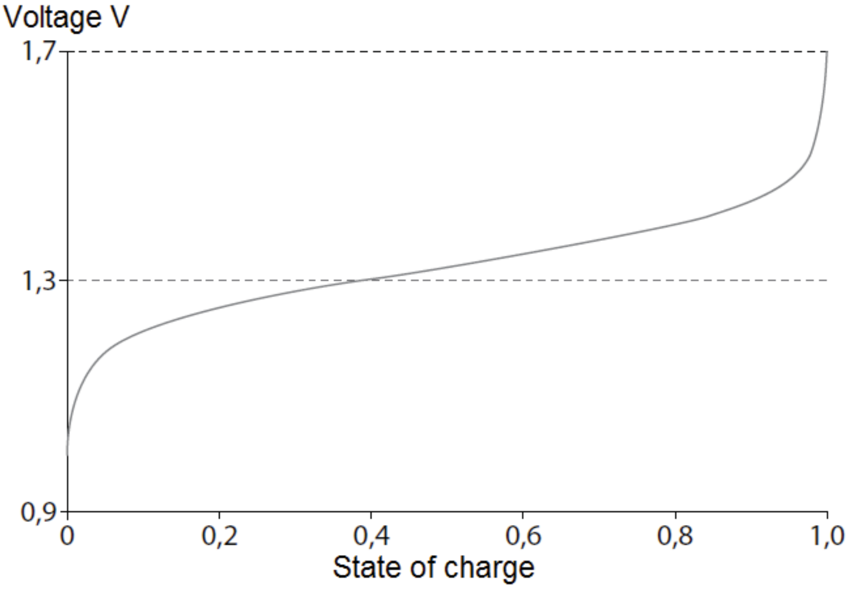
TABLE 7: TYPICAL VALUES FOR VANADIUM-REDOX-FLOW BATTERY CHARACTERISTICS

Battery Cell Characteristics	
Nominal cell voltage (V)	1.26 V (standard cell pot.) 1.4-1.6 V (50 / 100 % soc)
Round Trip Efficiency cell and system (%)	<90 % cell / 80-90 % system
Self-Discharge rate	very little, only electrolyte in cell, not in tank
Specific energy density of electrolyte	15-30 Wh/kg
Specific power density	Dependent on size/number of stacks
Minimum State of Charge (%)	10 % typical
Nominal power until state of charge (%)	Compare FIGURE 12
Max. Charge Rate (A/Ah)	Dependent on electrolyte tank and stack capacity
Discharge capacity characteristics	Compare FIGURE 13
Float life (yr)	~10 years
Cycle-life dependent on discharge depth	>200,000 cycles

SOURCE: GARCHE (2009), MOSELEY (2015), BECKER ET AL. (2015), STERNER; STADLER (2014)

The cell voltage of a Vanadium-redox-flow battery dependent on its state of charge is described by FIGURE 12, as published by Sterner; Stadler (2014).

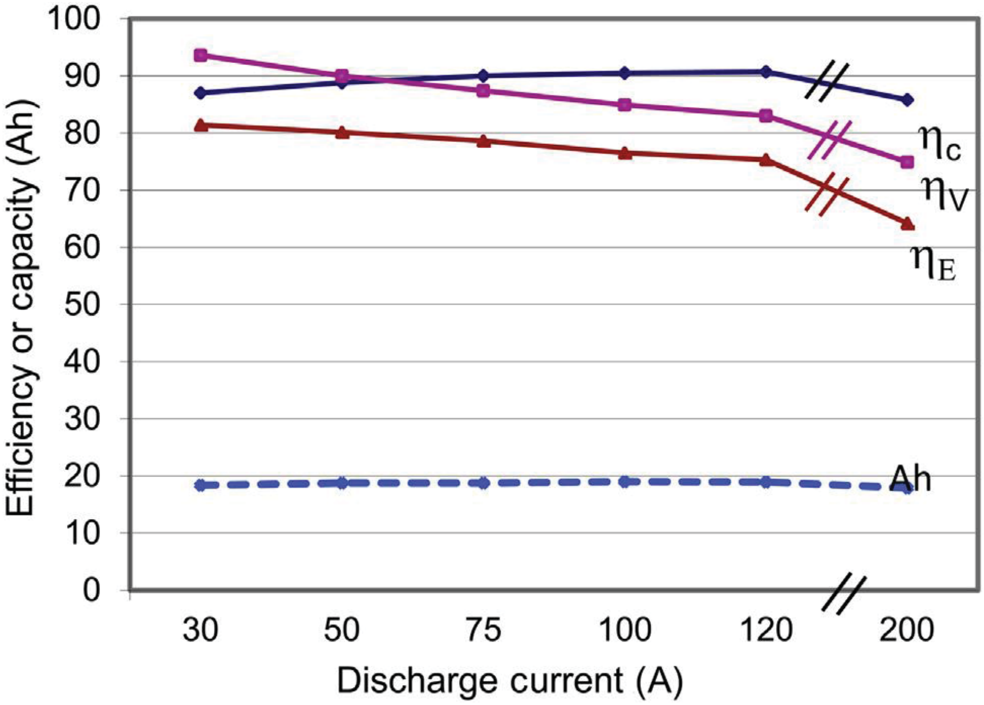
FIGURE 12: CELL VOLTAGE DEPENDENT ON STATE OF CHARGE FOR A VANADIUM-REDOX-FLOW BATTERY



Source: adapted from STERNER; STADLER (2014)

An example for relation between efficiency in terms of applied discharge current for vanadium-redox-flow battery is given in FIGURE 13 (MOSELEY, 2015). Where $\eta_C = \text{coulombic} -$, $\eta_V = voltage -$ and $\eta_E = energy\ efficiency$.

FIGURE 13: PLOTS OF COULOMBIC, VOLTAGE, AND ENERGY EFFICIENCIES AND CAPACITY AS A FUNCTION OF DISCHARGE CURRENT FOR A CONSTANT CHARGING CURRENT OF 30 A FOR A UNSW 2-KW/12-KWH G1 VRB STACK



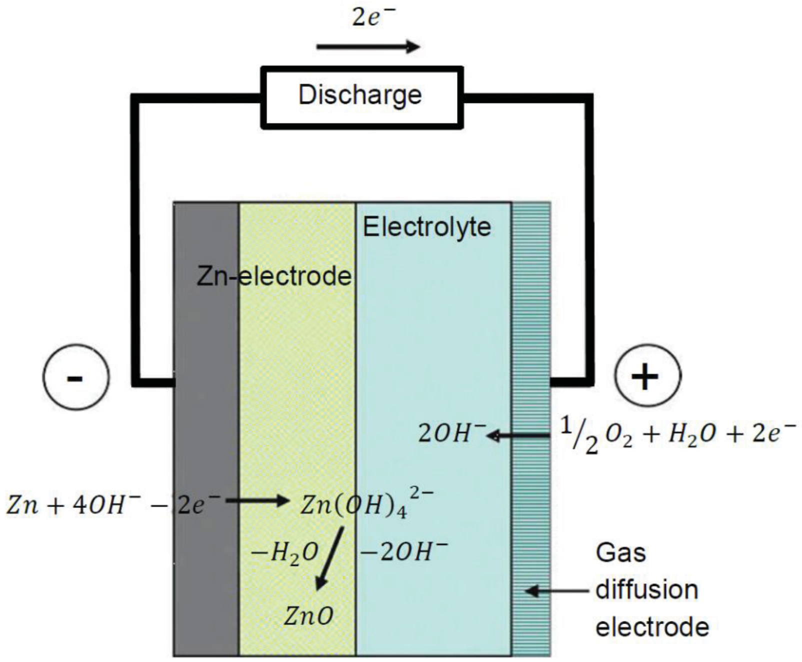
SOURCE: MOSELEY (2015)

Investment costs are given by Sterner; Stadler (2014) with 250 – 865 €/kWh or 710- 1790 €/kW respectively. There is no information given about operation costs.

2.2.5 Zinc Air Batteries

There are numerous types of metal-air batteries, whereby zinc-air batteries show the highest specific energy. Zinc works as negative electrode; oxygen as active material of the positive electrode and the electrolyte is typically concentrated potassium hydroxide. The principal components and electrochemical reactions of a zinc-air cell are described by FIGURE 14 as Garche (2009).

FIGURE 14: PRINCIPAL COMPONENTS AND ELECTROCHEMICAL REACTIONS DURING DISCHARGE OF A ZINC-AIR CELL



SOURCE: GARCHE (2009)

During discharge zinc (Zn) oxidizes with hydroxide $(4OH^-)$ to Zincate $Zn(OH)_4{}^{2-}$ at the negative electrode, releasing electrons, which float through the load to the positive oxygen electrode, see Equation 12. At the positive electrode oxygen (O_2) diffuses out of the air through the porous electrode and gets reduced by these electrons in aqueous media to hydroxide ions (nOH^-), compare Equation 13. The overall chemical reaction is described by Equation 14 as Garche (2009)

Negative electrode reaction:

$$Zn + 4OH^- \underset{charge}{\overset{discharge}{\rightleftarrows}} Zn(OH)_4{}^{2-} + 2e^-$$

EQUATION 12

Positive electrode reactions:

$$O_2 + 2H_2O + 4e^- \underset{charge}{\overset{discharge}{\rightleftarrows}} 4OH^-$$

EQUATION 13

Overall reaction:

$$2Zn + O_2 \underset{charge}{\overset{discharge}{\rightleftarrows}} 2ZnO$$

EQUATION 14

Theoretical standard cell voltage is represented by the difference of anode and cathode reactions, $V^\circ = |-1.266| + 0.401 = 1.667\,V$. In practice voltage range lies in the range of $0.9 - 1.3\,V$. A summary of some typical values for zinc-air battery characteristics is given in Table 8.

TABLE 8: TYPICAL VALUES FOR ZINC-AIR BATTERY CHARACTERISTICS

Battery Cell Characteristics	
Nominal cell voltage (V)	~1.2 V
Round Trip Efficiency cell and system (%)	60 % cell no information for system
Self-Discharge rate (% per day)	Rising rates with rising temperature, no data available
Specific energy density on cell level	200 Wh/kg; 100-200 Wh/dm³; (theoretic 1,100 Wh/kg)
Specific power density	100 W/kg; 50-100 W/dm³
Minimum State of Charge (%)	~20 %
Nominal power until state of charge (%)	No data available
Max. discharge Rate (A/Ah)	1 C
Max. Charge Current (A)	No data available
Discharge capacity characteristics	No data available
Float life (yr)	Indicated as low without further specification
Cycle-life dependent on discharge depth	~200 at 50 % dod

SOURCE: GARCHE (2009) MOSELEY (2015), REINER KORTHAUER ET AL. (2013)

Since most references cited by Garche (2009) are already about 20 years old the data for technical performance might not be representative for the actual state of the art. For example the company “eos energy storage” offers battery systems with a round trip efficiency of 75 %, compared to a cell efficiency of only 60 % as indicated by Garche (2009). Eos energy storage offers systems for about 160 – 200 $/kWh, information about operation costs is not given, EOS (2016).

2.3 REGULATORY FOR ELECTRICAL ENERGY STORAGE SYSTEMS

Regulatory policies and directives from the Brazilian Federal Government for the electricity sector are in responsibility of the national agency for electric energy - ANEEL (*Agência Nacional de Energia Elétrica*). In this chapter general information about the Brazilian electricity sector and relevant technical and economical regulations for battery system utilization in low and medium voltage level are summarized. Details about the general market and regulatory structures, quoted in this chapter, are adapted from Nery (2012). It is considerable that there are no specific regulations for electricity storage systems. Due to the basic, grid relevant functions of EES systems, which are load and generation, all technical and economical regulations are analysed to identify relevant sections. Technical regulations are split in generation, transmission, distribution and commercialization. Economic regulations are divided in terms of tariffs and market. The full set of all regulatory can be found online at ANEEL (2017a) website.

Electricity market actors

The Brazilian electricity sector is divided in five groups of actors, which are generation, transmission, distribution, commercialization and consumption. A short summary of definition and activities as explained in details by Nery (2012) is presented below.

- Generation: Generators can sell their generation capacity on the regulated or the free electricity market. On the regulated market commercialization is done via auctions, executed by the Electric Energy Trading Chamber - *CCEE (Câmara de Comercialização de Energia Elétrica),* a non-profit civil society.
    - Subsidised generators:
        - Small hydroelectric turbines, biomass plants, wind turbines, PV
        - Connected to transmission or distribution network
        - Maximum generation capacity of up to 50 MW
        - Generators with maximal 30 MW or 1 MW for hydro power can get a discount of 50-100 % on network usage cost as regulated by ANEEL, based on law n° 9.427 from 26th of December 1996, normative from ANEEL n° 77/04 and n° 247/06 for commercialization.
- Transmission Grid operators:
    - High voltage electricity network with 230 kV or more used to transport electricity from the generators until the distribution networks.
    - Sell network capacity to free consumers, generators and retailers.
    - Must guarantee transmission of contracted electricity quantity
- Distributors:
    - Supply electricity to captive consumers
    - Offer tariffs under regulation of the *ANEEL*
    - Buy electricity capacity at the regulated market in form of national auctions for generation capacity or on the free market directly from the generators.
    - are responsible for distribution network operation, maintenance and future planning
    - Have to provide future demand planning to National electricity system operator – *ONS (Operador Nacional do Sistema Elétrico)*.
    - Make direct contracts for reserve capacity
    - Sell network capacity to free consumers, generators and retailers.

  - A list of all distributers of the Brazilian electricity grid is published by ANEEL as available under: ANEEL (2017b).
- Commercialization:
  - Retailing companies buy generation capacities and sell these to free customers. Tariffs and conditions are negotiated direct between trading company and the customer.
- Consumption: Electricity consumers are divided in three types in respect to their contracting ambience, which can be or captive, special or free.
  - Consumers with a demand inferior to 3 MW are captive and must contract energy tariffs from their regional distributer.
  - An exception is made for special consumers with minimum demands of 0.5 MW, who buy electricity from subsidised sources connected to the distribution or transmission network.
  - The minimum demand of 0.5 MW must be approved as defined by ANEEL resolution n° 247.
  - Free consumers can select between tariffs from the local distributer or participation in the free electricity commercialization market. As free consumers electric energy can be bought direct from generators or retailers.

Commercialization of electric energy

There are different ways of energy commercialization, which follow captive or free commercialization rules.

- *PROINFA* – RE incentive program
- *CCEAR* – energy commercialization in regulated market
- *Leilão* – auction
- *CCEAR DISP* – energy commercialization in regulated market for capacity
- *Inicial* – commercialisations contracted before regulation reforms
- ITAIPU – Itaipu binational hydro power plant special regulations
- CCEAL – Contracts for buying energy in free ambient
- *Bilateral* – bilateral

PROINFA (Programa de Incentivo as Fontes Alternativas de Energia Elétrica) is an incentivisation program for alternative energy sources which include small hydro plants, biomass plants and wind turbines, which have started operation before 2011. The commercialization of this energy is realized via quotes for all distribution companies and free consumers.

CCEAR (Contratos de Comercialização de Energia do Ambiente Regulado) is divided in energy quantity and energy availability *(CCEAR – DISP)* contracts.

- Energy quantity
    - Generators are responsible for delivering of contracted energy quantity or compensation of additional cost for alternative, spot market generation. Distributers take the risk of differences in sub market prices.
- Energy availability
    - Generators get payed a yearly fixed price for availability, which covers all fixed costs of construction and standby for keeping a certain additional production capacity in standby. In case of request for this additional electricity generation by the *ONS* a variable payment per energy quantity is paid. The price for variable generation is calculated by the *CCEE* based on generator specific generation cost and current fuel prices.

CCEAL (Contratos de Compra de Energia no Ambiente Livre) is characterised by free market participants making bilateral contracts between generators, traders and consumers. Some information about contracted energy volume, duration, distribution over contracted time must be reported to *SCL*.

ITAIPU is treated separately due to its nature of bilaterality and contracts are made between the agent of ITAIPU energy commercialization and the distributors.

Auctions are the primary form distributers to buy generation capacities on the captive market. Distributers report their required generation capacities yearly to the ONS as expected for up to five years in advance. Based on this data the ONS prepares auctions for different time horizons. The auctions are published without information about required energy volume but containing a maximum acceptance price. During the auction the price is falling steadily until the amount of offered energy shrinks to the required volume. Therefore, the generators accepting the lowest price are winners. All distributers close a single contract involving all generators and resulting in an overall average electricity price for the respective auction. The auctions are divided under consideration of various factors, including: time of generation, generator technology, capacity and date of first generation. Main division of auctions are in terms of existing of new enterprises and reserve energy.

Generation versus load deviations:

Volume of traded energy is based on expected availabilities of generation capacities and demand. Therefore, mechanisms to cope with deviations are required. There are different methods to deal with divergences between contracted volumes of energy and actual demand.

One form is the MCSD *(Mecanismo de Compensação de Sobras e Déficits)* mechanisms, which allow the distributers to offer exceed energy generation to other distributors, which face a shortage of contracted generation compared to actual demand. If there is still a surplus of energy, it goes back to the generator. This can be made monthly *(MCSD Mensal)*, in form of free exchange *(MCSD Trocas Livres)*, via the yearly possibility of up to 4 % electricity market dynamic compensation *(MCSD 4 %)* regulation, an ex-post equilibration mechanism to compensate distributors for eventual losses due to over capacities sells for selling prices below buying and protecting distributors from penalties caused by demand shortages *(MSCD Ex-post)* or a separate model in case of Itaipu *(MCSD de Itaipu).*

Real time generation dislocations can be used to shift over and under production between generation plants and sub markets, what is known as Energy reallocation mechanism – *MRE (Mecanismo de Realocação de Energia)* to maintain the grid balanced. Participation in this reallocation mechanism is obligatory for dispatch able hydro power plants and optional for the others. A continuous control mechanism is applied to verify promised and realized dispatch ability of participating plants, the so called *MRA (Mecanismo de Redução de Energia Assegurada)*.

Electricity price formation:

The formation of electricity prices is shaped by its nature of generation resource construction and build around the price of liquidation of differences - PLD (*Preço de liquidação das diferenças*).

The Brazilian electricity system is dominated by hydroelectric generation, which offers the lowest marginal generation cost but is limited by the quantity of water available. A centralized optimization program is used by the national operator of the electricity system - *ONS (Operador Nacional do Sistema Elétrico)* to control the energetic use of water reservoirs in view of overall, long term generation cost minimization and security of supply. Whenever the marginal costs of alternative generation are lower than the long term predicted overall generation cost without alternative generation at the observed, current time, alternatives are used, and water reserves are hold back via a merit order hydro shut down strategy. This marginal operation cost - *CMO (Custo Marginal de Operação)* is defined by the cost of generation of the next MWh of energy capacity, calculated via the long, medium and shot term planning model of hydro thermal system operation (*Newave* and *Decomp*), and also It defines the liquidation price PLD, which is known as spot price.

PLD can vary between submarkets in case of regional energy shortages which cannot be compensated sufficiently by use of transmission network and lead to utilization of costlier thermos power plants in the affected submarket. Also, electrical restrictions, which are not considered by the ONS during the calculations of lowest overall, long term cost generator operations, can lead to changes of the dispatch plan and therefore different generation costs in submarkets. These situations lead to compensation for both parties, which are defined as charges for system services *ESS1 - (Encargos de Serviços de Sistema)* and calculated separately for each submarket. Shut down generators which were foreseen for production (constrained-off) as well as operated generators which were planned to stay in standby (constrained-on). Another motivation for the *ONS* to violate the calculated lowest generation cost merit order operation of generators can be in terms of obtaining system security, in accordance with Resolution CNPE n° 8 from 2007 *(Resolução CNPE n° 8, de 2007)*.

Auxiliary and security system services

Auxiliary services are measures taken to maintain system integrity and quality of the electricity network within defined limitations, in the Brazilian case regulated by *ANEEL*. These services include activities as:

- Standby reserve
    - Thermoelectric plants available for fast start of generation. Costs are compensated according to *ESS-1* regulations, authorized by *ANEEL*.
- Synchronous compensation of reactive energy
    - Authorized plants get compensation for service in relation to produced or consumed volume of reactive energy
    - Costs compensated by *ESS-1* regulations cover also required system adaptions including installation and maintenance of automatic generation control, special protection and Black Start systems.
- Violation of merit order generator operation to guarantee system security

    - Compensation of extra costs is remunerated by charge for energy security *(Encargo por Segurança Energética)*.

Penalties for electricity market actors

Thera are various risks of penalties for energy market actors, which include:

- Generators
    - Lack of fuel
- Energy provider
    - contracted volume bought inferior to sold
    - contracted power sold inferior to available
- Free consumer
    - consumption superior to contracted volume
- For all actors
    - Metering anomalies
    - Fines for failure to provide financial guarantees calculated based on risk that actors add to the market

Regulated vs free electricity market

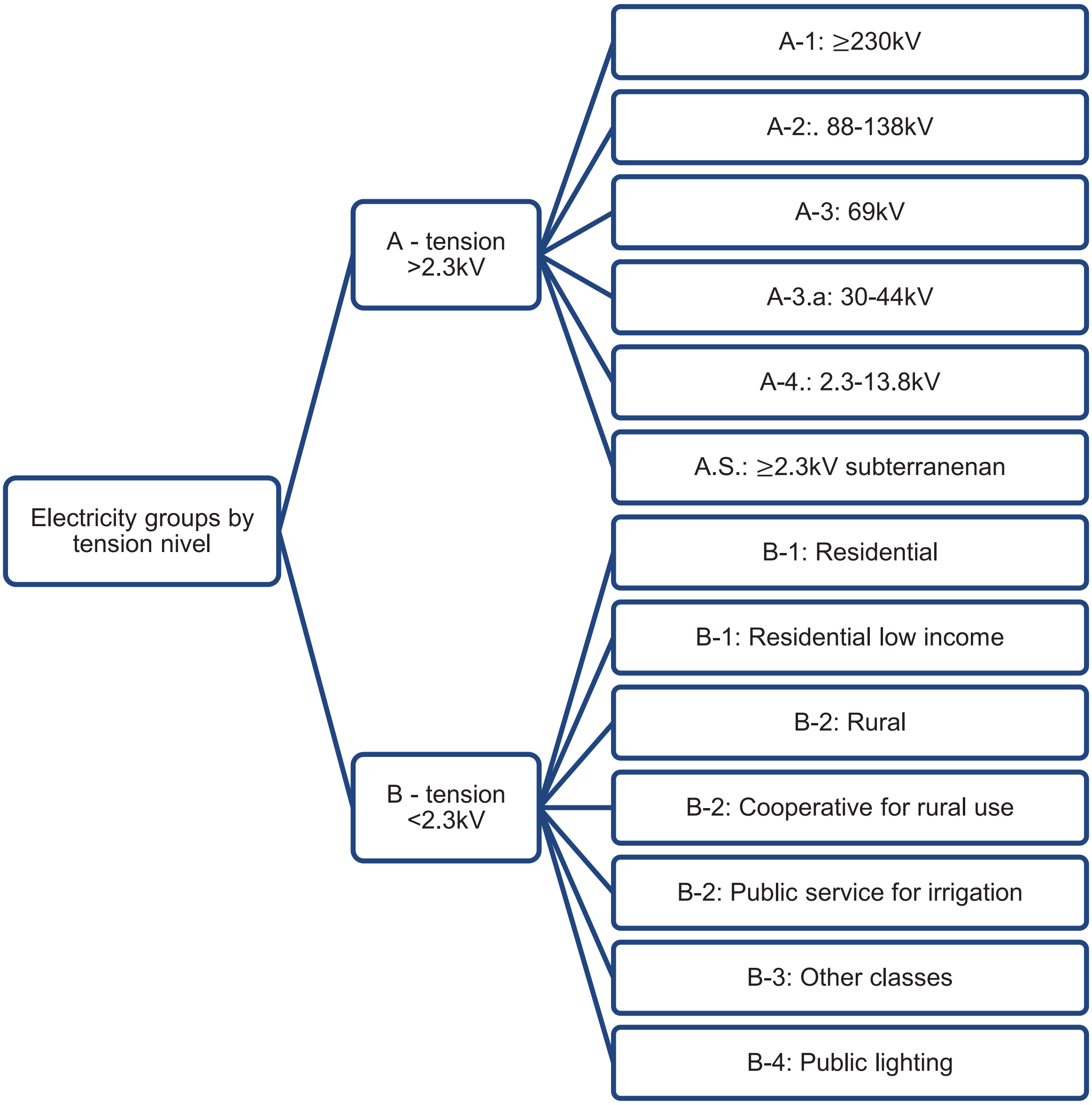
The regulated market ACR (*Ambiente de Contratação Regulada*) is destined to attend all captive customers, which cannot choose where to buy their electricity but are dependent on the distributors. Distributers are in charge for the distribution grid infrastructure and adequate electricity supply to all captive consumers and can obtain electricity from the regulated as well as from the free market, whereby the major volume consists of contracts from auctions. Electricity prices are the result of auctions

The free market ACL *(Ambiente de Contratação livre)* instead is only available for free customers who meet the relevant requirements which can choose where to buy their electricity, what can be either directly from the generators or via traders. Conditions of electricity contracts can be negotiated individually and direct between traders and consumers but include an inflexible part for the use of distribution and transmission grid utilization as well as a participation in promoting programs in the same way as captive consumers do.

Electricity Tariffs:

Tariffs can be structured dependent on different characteristics, which include generally customer type and voltage level. Electricity tariffs for captured consumers, as offered by the distributors are equal for all areas. There are various customer classifications, working as a political instrument to support institutions of public interest or low-income customers, offering different tariff models and price levels. In this way customer classes receive or contribute to expansion and simplification of access to electricity and rural development. The division of electricity tariffs, based on voltage level of customer connection, as used in the Brazilian energy market is demonstrated in FIGURE 15.

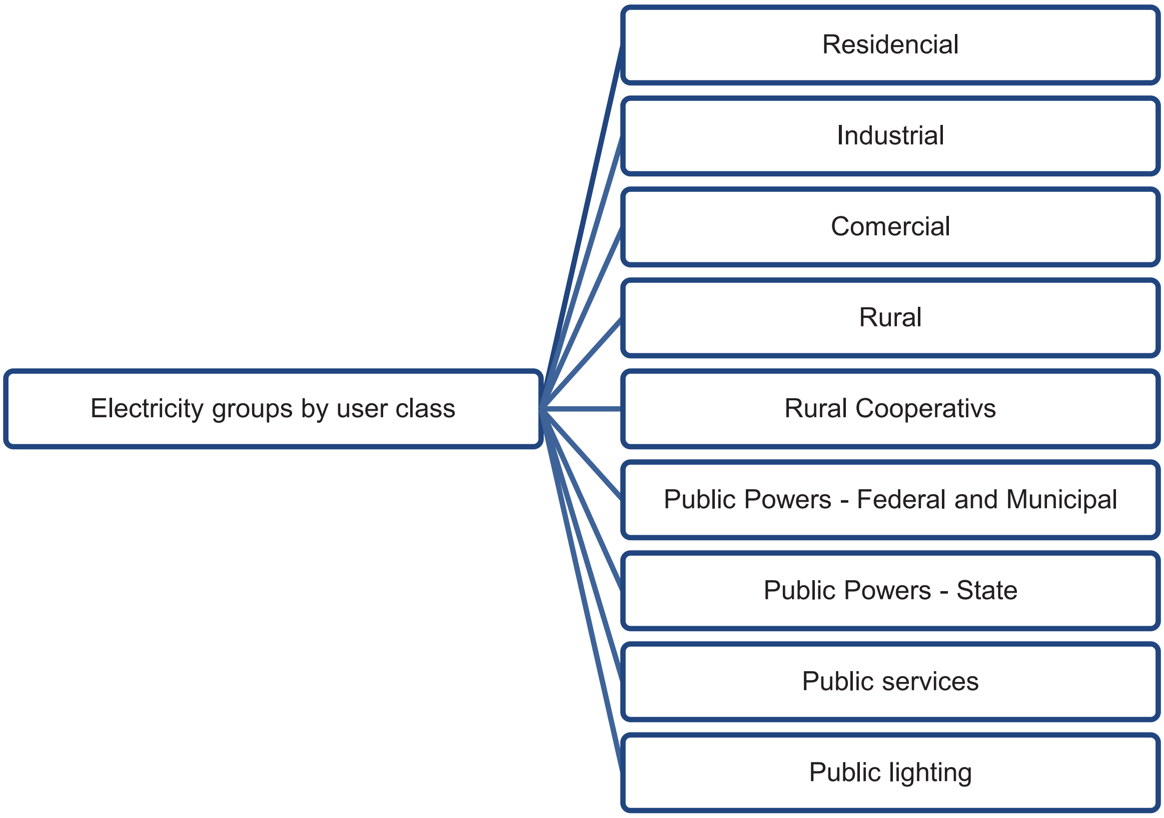
FIGURE 15: ELECTRICITY TARIFF CLASSES DIVIDED BY VOLTAGE LEVEL



SOURCE: Adapted from Nery (2012)

High voltage tariffs are characterized by a fixed, monthly payment for required maximal power capacity as well as a demand specific price per consumed electricity capacity. In comparison low voltage tariffs only consist of payments for consumption. An overview of different consumer types is given in FIGURE 16.

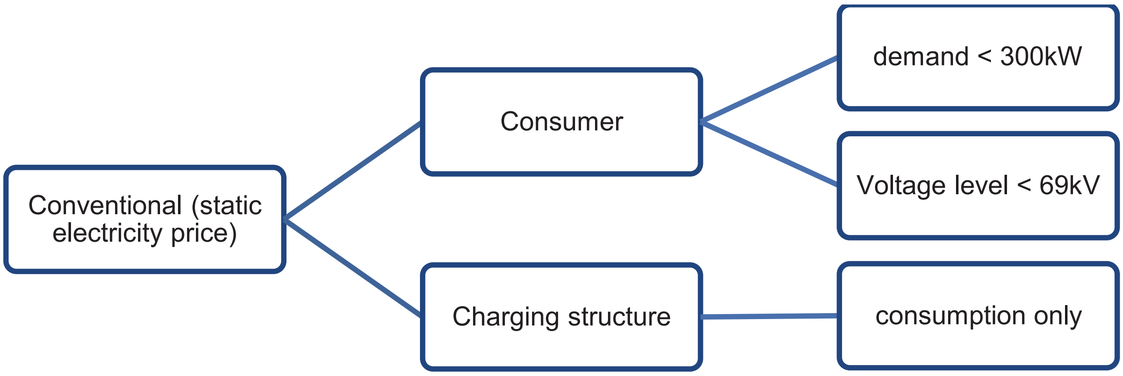
FIGURE 16: OVERVIEW OF DIFFERENT ELECTRICITY CONSUMER TYPES



SOURCE: Adapted from COPEL (2017) (access date 4th of April 2017)

Besides being bound to voltage level and consumer type definitions, the captive customers can decide between two basic forms of tariffs. First type is known as the conventional tariff, which offers a constant electricity price per consumed energy volume, independent of time of consumption, see FIGURE 17.

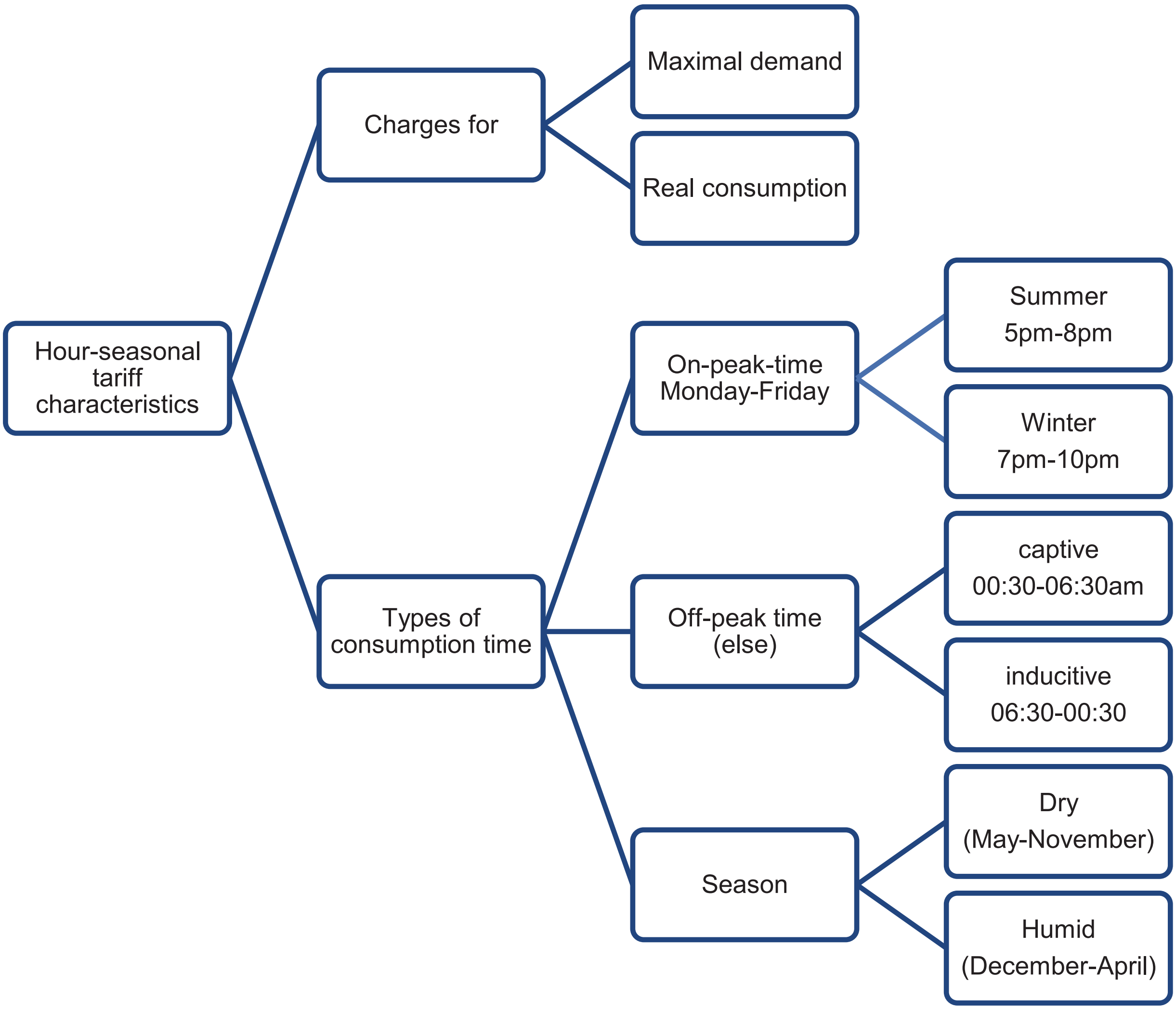
FIGURE 17: CONVENTIONAL TARIFF CHARACTERISTICS



SOURCE: Adapted from Nery (2012)

The second type is a time, day and season depending tariff model, called THS *(Tarifa horo-sazonal)* and is obligatory for consumers connected to the grid at a voltage level superior to 2.3 kV. The applied criteria, to compose the structures of hour-seasonal tariffs, are given in FIGURE 18.

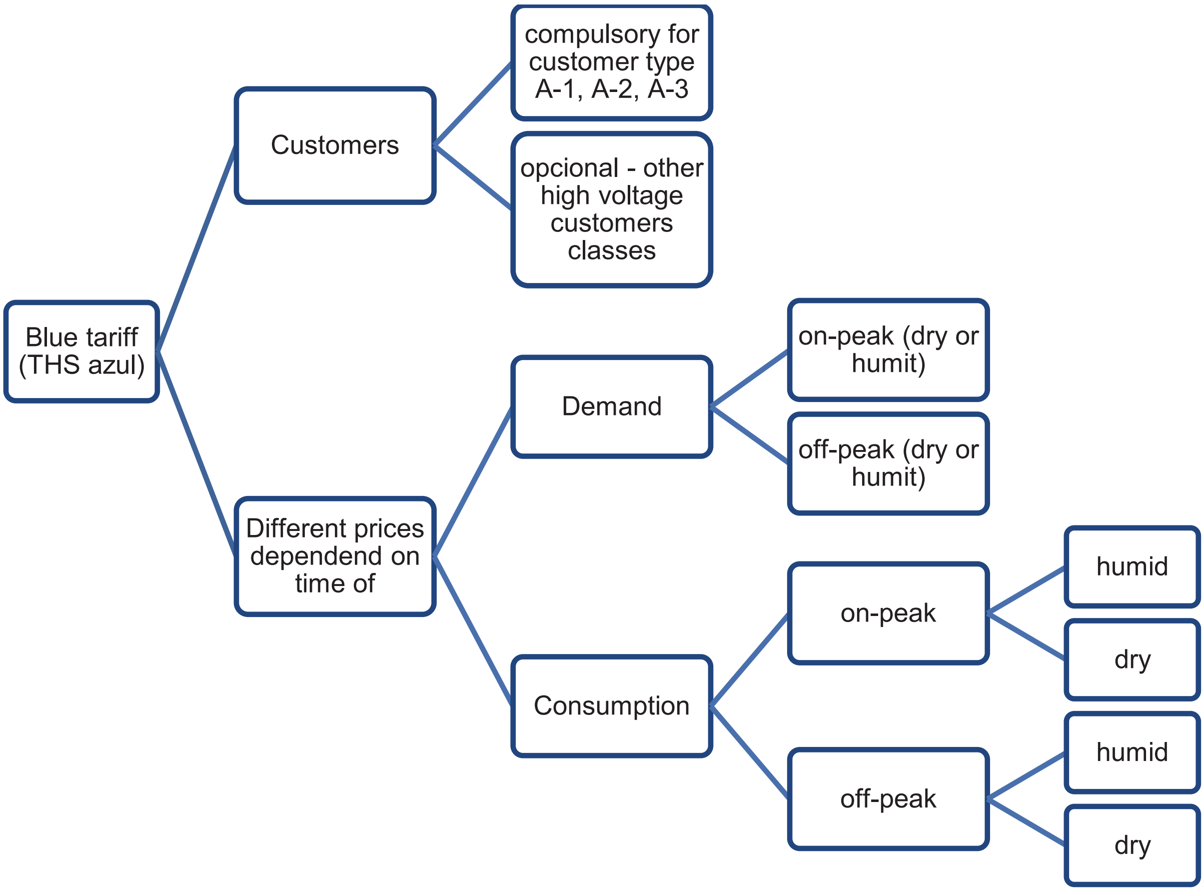
FIGURE 18: OVERVIEW OF HOUR-SEASONAL TARIFF CHARACTERISTICS



SOURCE: Adapted from Nery (2012)

The hour-seasonal tariff is further divided into the blue *(tarifa azul)* and the green *(tarifa verde)* tariff. The blue tariff is obligatory for customers connected to the grid at a voltage level of at least 69 kV and optional available to all other high voltage customers. The tariff is recommended for customers with high on-peak load characteristics, having the possibility to shift these into off-peak time. The scheme of relevant input parameters for electricity price calculation within the blue tariff is given in FIGURE 19.

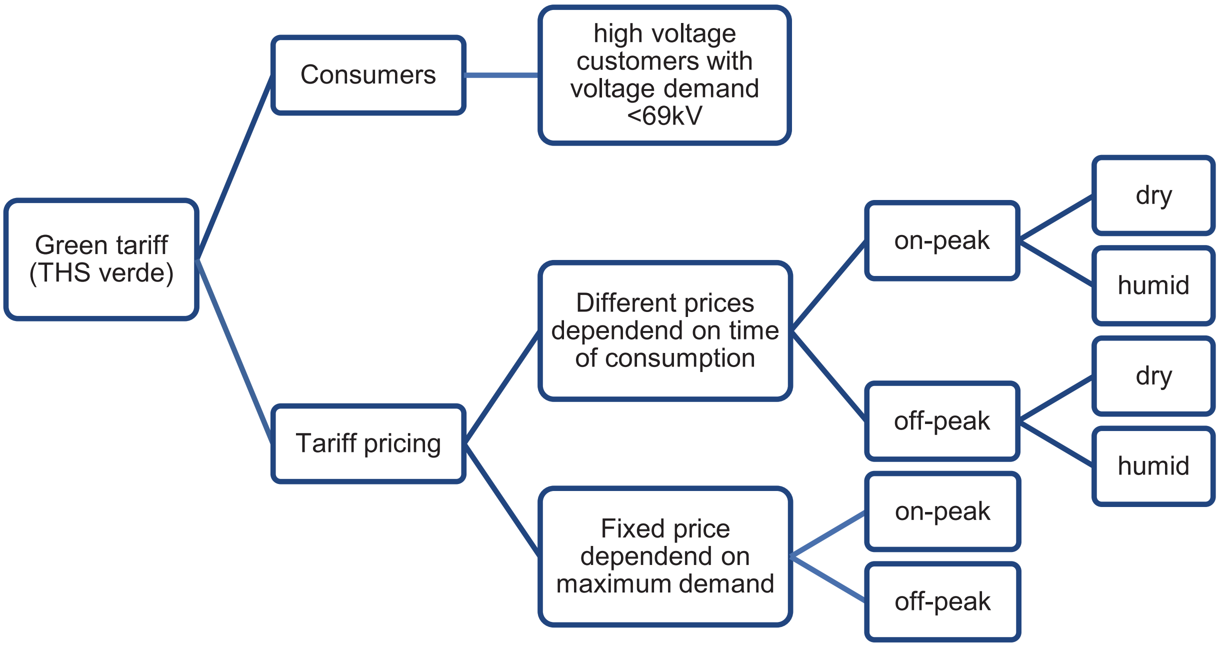
FIGURE 19: BLUE TARIFF PRICE FORMATION SCHEME



SOURCE: Adapted from Nery (2012)

The green tariff is available for high voltage customers with demands below 69 kV and recommended for consumers with low on-peak load and low shifting possibilities. The tariff is characterized by two fixed, season independent, monthly fees for the maximum load demand during on- and off-peak time and flexible prices for real consumption under consideration of all (daytime, day and season) timing factors. The scheme of relevant input parameters for electricity price calculation within the blue tariff is given in FIGURE 20.

FIGURE 20: GREEN TARIFF PRICE FORMATION SCHEME



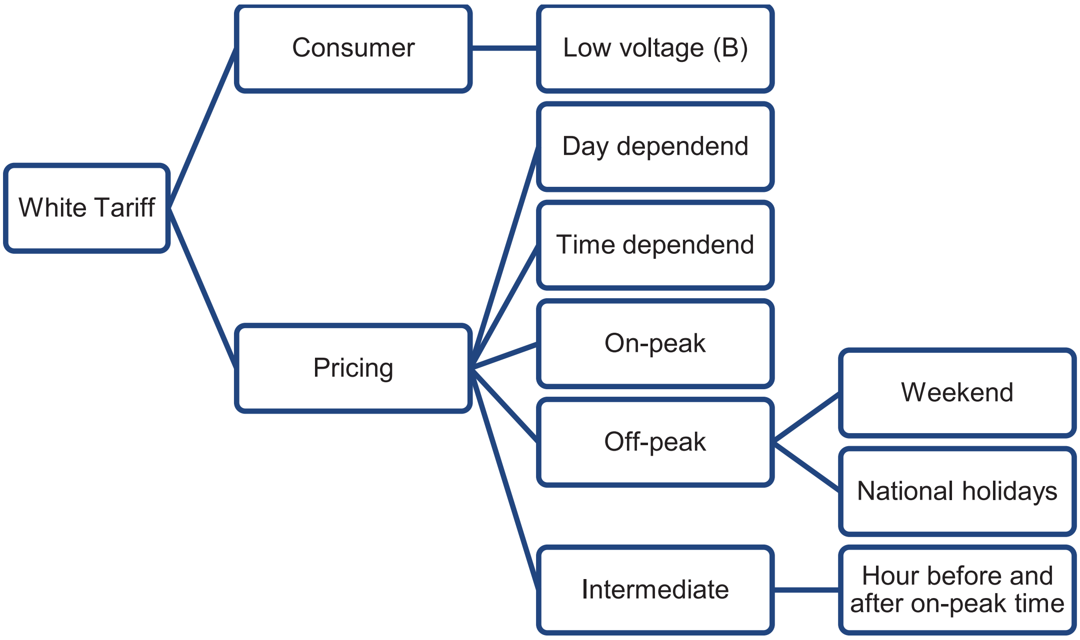
SOURCE: Adapted from Nery (2012)

It is notable that violation of contracted demand beyond tariff specific tolerances results in much higher rates and an economical advantageous tariff selection requires an accurate prediction of the real load.

The final allocation of consumers to a corresponding tariff is realized under consideration of installed load, provided tension, consumer class and the location and the catalogue of tariffs also includes various types offering social and development incentivisation discounts.

The white tariff (*tarifa branca*) is a time depending electricity tariff model for B-class, low voltage, clients. The tariff offers low rates for off-peak hours, below the conventional tariff, in combination with higher tariffs during the on-peak period and intermediate prices during the hour before and after the on-peak time. This intent to motivate customers to change consumption behaviour by shifting consumption from critical on- to calmer off-peak hours, what brings positive impacts on electricity network utilization. Actual information about tariff schedule and prices is published online at ANEEL (2017c). An overview of basic white tariff structures is given in FIGURE 21.

FIGURE 21: WHITE TARIFF CONSUMER AND PRICING SCHEME



SOURCE: ANEEL (2017c)

Distributed generation and micro girds

As described in ANEEL (2016a), distributed mini and micro generators are regulated by normative n° 482 *(Resulução Normativa n° 482, de 17 de abril de 2012)*, updated by 687 *(Resulução Normativa n° 687, de 24 de novembro de 2015)* from ANEEL, which regulates the operation of small generators for grid connected self-generation and energetic exchange of electric energy over a longer time horizon. Distributed generators can offer positive effect on the electricity network, such as investment postponement, voltage stability during peak hours, low environmental impact and contribution to energy matrix diversification. But they introduce also alteration in network operation, metering, control and protection procedures.

Distributed generators falling under these regulations are:

- Connected to the distribution grid at a consumer site
- installed capacity ≤ 75 kW - micro generators
- 75 kW ≤ installed capacity ≤ 3 MW / 5 MW (hydro/other) – mini generators

Distributed generators get injection priority by the distributor compared to other generators. All necessary steps and deadlines from request of connection until start of operation are regulated to ensure fast project realization times. The distributor is responsible for generation data collection for micro and mini generation systems and in case of micro generation also carries the total costs for metering. Responsibility for eventual required grid reinforcements is regulated between distributor and the consumer, requesting for distributed micro/mini generator connection.

It is notable, that the regulations explicit define that the grid is supposed to work as a tool of storage, absorbing excess distributed micro and mini generation and delivers this amount back to the generator-connected consumption unit or a pre-defined consumer partner, located within the same concession area, at any time of need within 60 months. This can be reached under different constellations between consumer and generation units, being within the definition of: A group of consumer units of the same or different owner can share direct or under organisation of a third party one or more generation units, located at any place within the same concession area *(geração compartilhada, autoconsumo remoto, condomínios).*

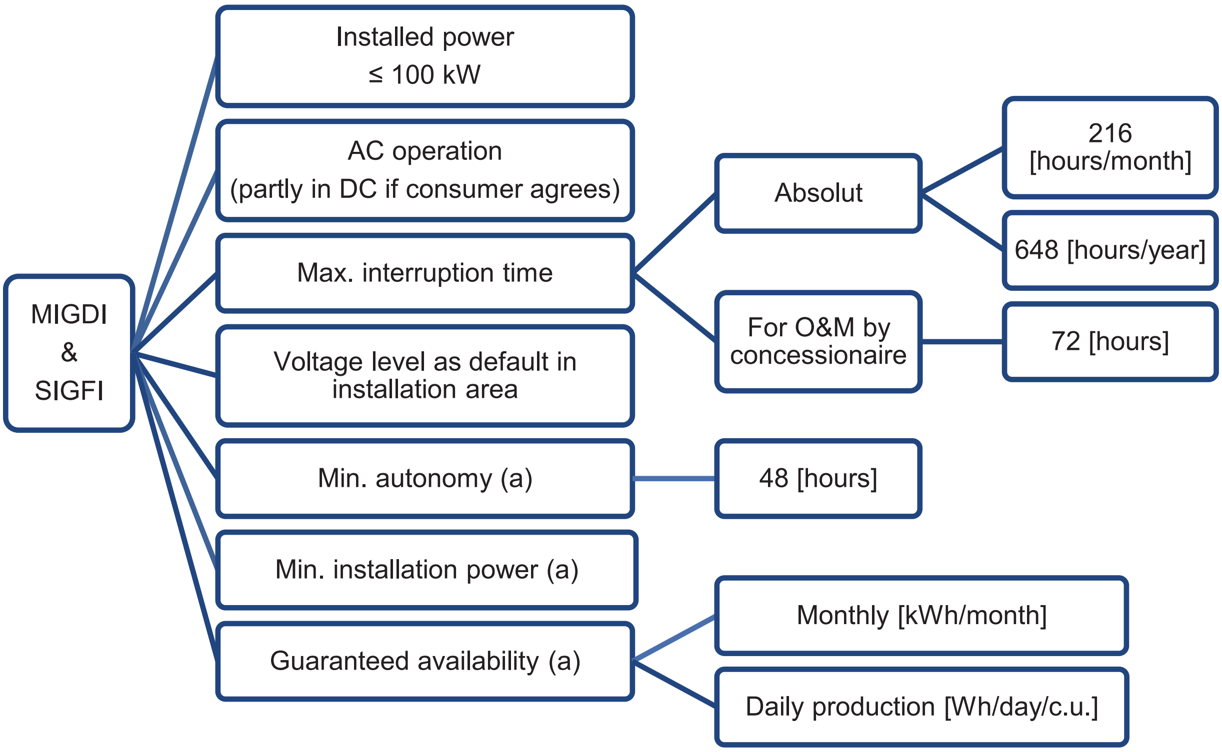
Even so, once connected and in interaction with the electricity network, the distributed generation becomes somehow a market participant and therefore needs to contribute to the taxation system. Depending on the state, trading taxes for the movement of goods and services, called *ICMS (Imposto sobre circulação de mercadorias e serviços),* for the total amount of electricity delivered by the gird to the consumer or at least for the balance between monthly generated and injected amount, incur. These taxes vary between state and consumer type. Current values can be accessed at ABRADEE (2017). Federal taxes for social integration and security, called *PIS and COFINS (Programas de Integração Social / Contribuição para Financiamento da Seguridade Social*), are to be paid for the positive difference between energy consumption and injection. The actual value, which is unique for the whole country, can be accessed online under EDP (2017).

Also, there is still a monthly fee of availability to be payed to the distributors, which is without changes for the tariffs from the classes A but new for the classes B. These must pay a value equal to the electricity consumption price of 30 kWh for monophasic, 50 kWh for biphasic or 100 kWh for three-phase connection respectively.

Normative n °493 from ANEEL, ANEEL (2012a), regulates the proceedings and conditions for generation and distribution within isolated micro systems (*Microssistema Isolado de Geração e Distribuição de Energia Elétrica – MIGDI*) and individual generation with intermittent sources *(Sistema Individual de Geração de*

Energia Elétrica com Fonte Intermitente – SIGFI). These systems are supposed to be installed by the distributer and respect certain regulations as shown in FIGURE 22.

FIGURE 22: REGULATIONS FOR MIGDI AND SIGFI CONFORME ANEEL NORMATIVE N °493



SOURCE: ANEEL (2012a), (a) dependent on system size as shown in TABLE 9

Reference systems, representing minimum values for installed power, guaranteed energy availability and autonomy are presented in TABLE 9.

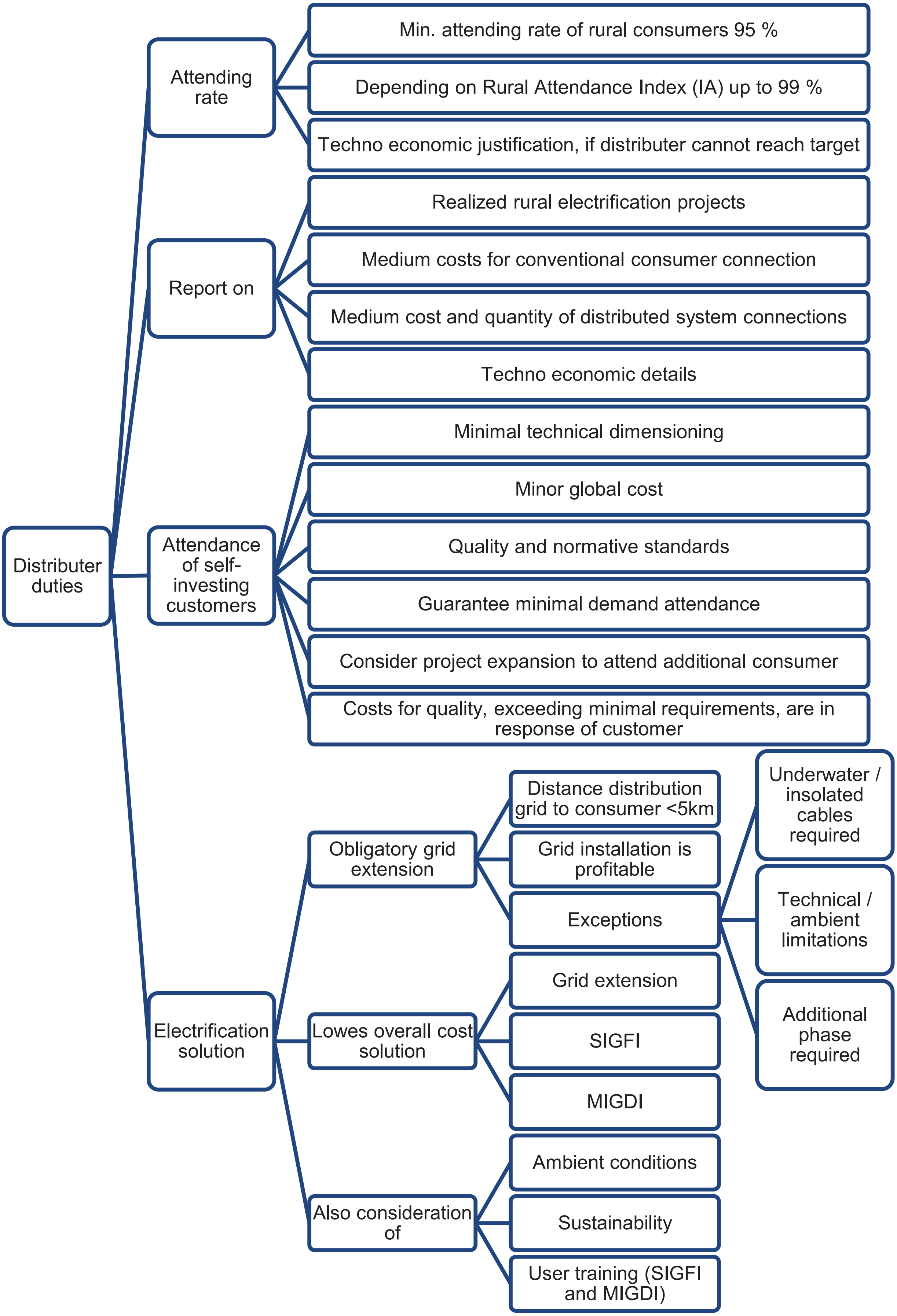
TABLE 9: REFERENCE CONSUMER UNIT (C.U.) DIMENSIONS FOR MIGDI AND SIGFI

Guaranteed monthly availability [kWh/month/c.u.]	Reference consumption [Wh/day/c.u.]	Minimal Autonomy [hours]	Minimal installed power [W/c.u.]
13	435	48	250
20	670	48	250
30	1	48	500
45	1.5	48	700
60	2	48	1
80	2.65	48	1.25
>80	Monthly consumpt./30	48	Case specific

SOURCE: ANEEL (2012a)

Normative n °488 from ANEEL, ANEEL (2012b), establishes the conditions for universalization of electricity distribution services in rural areas. The distributers, as public service actors, are obliged to make progress in rural electrification, including the criteria summarized in FIGURE 23.

FIGURE 23: NORMATIVE N° 488 DISTRIBUTER DUTIES ON RURAL ELECTRIFICATION



SOURCE: ANEEL (2012b)

3 LITERATURE REVIEW

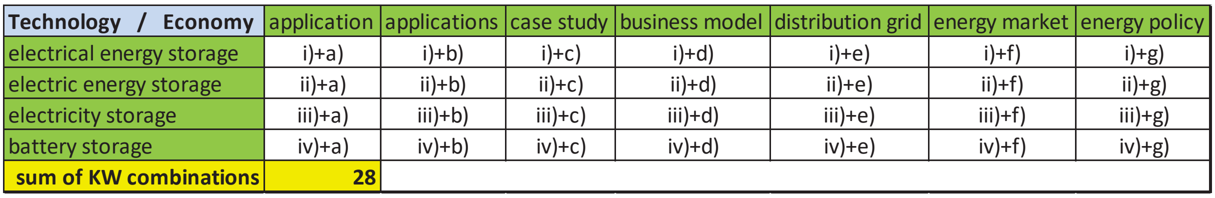
Target of this dissertation is to identify how battery storages might contribute to a more energy and cost-efficient electricity system. Therefore, existing applications and respective business cases for battery storage technologies as well as their characteristic, operational parameters must be collected and their viability within the Brazilian electricity market analysed.

3.1 PROCESS OF LITERATURE SELECTION

Ensslin et al. (2010) developed a bibliometric analysis process for scientific working which is used in a simplified way in this dissertation. An English translation of the full process can be found in Annex 2.

The collection of scientific articles analysed in this dissertation is done via the periodicals website from the Higher Education Personnel Improvement Coordination (*Coordenação de Aperfeiçoamento de Pessoal de Nível Superior-CAPES*) provided by the Brazilian ministry of education (*Ministério da Educação-MEC*), available under CAPES (2017) website. The search combines two main topics, which are energy storage and business. Four keywords for energy storage and seven for business are defined by brainstorming and pre-reading of articles identified as relevant for this research. Respectively 28 keyword combinations are used for the literature research as shown in TABLE 10.

TABLE 10: KEYWORDS FOR SEARCH OF JOURNAL ARTICLES



Technology / Economy	application	applications	case study	business model	distribution grid	energy market	energy policy
electrical energy storage	i)+a)	i)+b)	i)+c)	i)+d)	i)+e)	i)+f)	i)+g)
electric energy storage	ii)+a)	ii)+b)	ii)+c)	ii)+d)	ii)+e)	ii)+f)	ii)+g)
electricity storage	iii)+a)	iii)+b)	iii)+c)	iii)+d)	iii)+e)	iii)+f)	iii)+g)
battery storage	iv)+a)	iv)+b)	iv)+c)	iv)+d)	iv)+e)	iv)+f)	iv)+g)
sum of KW combinations	**28**						

SOURCE: The author

Considering only articles published within the last ten years and filtering the results for doubling the final gross database is obtained, as shown in TABLE 11.

TABLE 11: OVERALL FOUNDING FOR KW COMBINATIONS

Technology / Economy	application	applications	case study	business model	distribution grid	energy market	energy policy
electrical energy storage	223	350	66	13	33	64	23
electric energy storage	321	440	133	41	53	137	163
electricity storage	76	81	109	31	35	127	115
battery storage	485	509	73	29	25	69	35
sum of article foundings	**3.859**						

SOURCE: The author

All findings shown in TABLE 11 pass the first pre-selection step of title reading, where only the articles with titles fitting to the surge terms are selected, as shown in TABLE 12.

TABLE 12: PRE-SELECTED ARTICLES BY TITLE READING

Technology / Economy	application	applications	case study	business model	distribution grid	energy market	energy policy
electrical energy storage	12	14	12	6	7	13	1
electric energy storage	9				4	1	6
electricity storage	2		6	2	3	10	9
battery storage	32	29	9	1	5	5	5
sum of pre selected articles without doublings	**203**						

SOURCE: The author

All remaining articles pass the following step of selection by abstract reading, whereby all articles which turn out not to treat the focus of this work are sourced out of the literature research database. The leftover of 72 articles which seem to contain important information for this thesis are shown in TABLE 13 and need to be read as the next literature selection process step.

TABLE 13: ARTICLES SELECTED BY ABSTRACT READING

Technology / Economy	application	applications	case study	business model	distribution grid	energy market	energy policy
electrical energy storage	6	4	0	2	4	5	0
electric energy storage	4				0	0	1
electricity storage	0		2	1	2	6	5
battery storage	11	7	1	0	4	2	5
sum of pre selected articles without doublings	**72**						

SOURCE: The author

Relevant articles are finally read and summarized, highlighting relevant information in the context of this thesis. In addition to the articles, found along the presented literature research process, further sources of relevance are added to complete the description of the state of the art in respective area of research and development.

3.2 ESS TECHNOLOGIES, APPLICATIONS AND BUSINESS MODELS LITERATURE REVIEW

In this chapter the findings in literature are summarized, divided in two parts, which are first about existing ESS technologies, their technical characteristics under operation in different applications and second knowledge about relevance and influences of electricity market structures to ESS performance and approaches and methods for appropriate business models' creation processes. TABLE 14 and TABLE 15 inform about selected articles, authors, key words, journal and sequence of summary.

TABLE 14: SELECTED ARTICLES FOR STATE OF THE ART LITERATURE RESEARCH

Citation	**Key words**	**journal**
Poullikkas (2013)	Batteries; Energy storage; Power generation; Renewable energy sources	Renewable and Sustainable Energy Reviews
Ferreira Lopes et al. (2013)	electricity systems evolution; energy storage systems; renewable energy integration	Energy
Kear et al. (2011)	cost analysis; energy policy; energy storage; modelling; redox flow battery; vanadium	International Journal of Energy Research
Bradbury et al. (2014)	Arbitrage; Energy storage; Power markets	Applied Energy
Nottrott et al. (2013)	Economics; Energy storage; Forecasting; Optimal scheduling; Solar power generation	Renewable Energy
Manchester et al. (2013)	Energy; Interconnection; Storage; Tidal; Turbine; Wind	Energy
Carrasco et al. (2014)	Batteries; Degradation; PV modules; Reliability; Rural electrification	Energy
Tan et al. (2013)	Control strategy; Energy storage; Microgrid; Power electronics interface; Trends and challenges	International Journal of Electrical Power and Energy Systems
Turker et al. (2013)	Modeling; System efficiency; vanadium redox flow battery	Energy Conversion and Management

SOURCE: The author

TABLE 15: SELECTED ARTICLES FOR STATE OF THE ART LITERATURE RESEARCH, CONTINUATION

Citation	Key words	journal
Battke et al. (2013)	Energy storage; Levelized costs of electricity (LCOE); Monte Carlo simulation; Techno-economic modeling; Uncertainty	Renewable and Sustainable Energy Reviews
Krieger et al. (2013)	Capacity fade; Lead-acid; Lithium-ion; Off-grid renewables; Variable charge; Wind	Energy
Nykamp et al. (2014)	(Decentralized) storage systems; Battery; Break-even analysis; Capital recovery factor; Distribution grids; Photovoltaic; Renewable energy generation	International Journal of Energy Research
Pietila et al. (2012)	Air-conditioning (cooling); Electric loads; Housing; Zero peak housing	Building and Environment
Higgins et al. (2014)	Choice-diffusion model; Price tariffs; Solar photovoltaic	Energy
Paine; Homans, Frances R.; et al. (2014)	Electricity markets; Energy market rules; Energy storage; Independent system operator; Pumped hydro; Reliability services	Energy Economics
Behrangrad (2015)	Business model; Demand response; Demand side management; Electricity market; Energy efficiency; Renewable energy; Smart grid	Renewable and Sustainable Energy Reviews
Anuta et al. (2014)	Electricity market; Energy storage systems; Policy; Regulation; Renewable energy; Transmission and distribution networks; Unbundled electricity system	Renewable and Sustainable Energy Reviews
Poudineh; Jamasb (2014)	Business model; Demand response; Distributed generation; Investment deferral; Network regulation; Storage	Energy Policy
Battke; Schmidt (2015)	Innovation; Learning curve; Profitability; Subsidy; techno-economic model; vanadium redox flow battery	Applied Energy
Taylor et al. (2013)	Energy storage; Low-carbon energy system; Socio-technical transitions	Energy Policy
Jingwei Zhu, Michael Z. Q. Chen, Baozhu Du (2014)	n.a.	Journal of Applied Mathematics

SOURCE: The author

3.2.1 ESS technologies, applications and characteristics

A summary of relevant articles about distributed battery technologies and applications, cited in this thesis, is given in TABLE 16.

TABLE 16: LITERATURE ABOUT BATTERY TECHNOLOGY AND APPLICATION SUMMARY

Source	Battery Type	Application	Main results
Poullikkas (2013)	LA, li-ion, Ni-Cd, NaS, vrf, ZnBr	Ancillary services, RE integration, electricity Quality	Technologies and applications for large scale ES utilization
Ferreira Lopes et al. (2013)	LA, Ni-Cd, NaS, flow, met.-air	Distributed storage, electricity quality	Currently economically not viable, insufficient remuneration of ancillary services
Kear et al. (2011)	VRF	Electricity quality, RE integration, distributed storage	Economical not jet viable, RE+Subsidies+Battery could be viable
Bradbury et al. (2014)	LA, Ni-Cd, li-ion, ZEBRA, NaS, VRF, ZnBr	Arbitrage	Optimal Capacity at ≤4h
Nottrott et al. (2013)	Li-Ion	On-Grid PV Dispatch	Economic Advantages with Demand/Generation Forecast & BEP at 450$/kWh
Manchester et al. (2013)	n.c.	RE Generator Implementation under Grid Capacity Limitations	Overall provide optimization by ESS operation
Carrasco et al. (2014)	LA	Rural PV-Battery Electrification	Manufacturer quality main reason for Battery degradation, End of Life defined by consumer satisfaction, PV is Mature Technology
Tan et al. (2013)	LA, NiCd, NaS, NiMH, Li-ion	ESS in Micro Grids	Cost still too high for grid scale ESS integration
Turker et al. (2013)	VRF	n.c.	Operation scheme great impact of efficiency
Battke et al. (2013)	LA, Li-ion, NaS, VRF	Electricity quality, self-consumption, investment deferral, utility energy time-shift	NaS lowest cost in energy applications, Li-ion in power applications
Krieger et al. (2013)	LA, LCO, LCO-NMC, LFP	Off-grid + wind turbines	LA high degradation due to sulphation and resistance growth LCO less sensitive. LCO-NMC better performance and LFP best alternative.
Nykamp et al. (2014)	n.c.	ESS as alternatives to gird investment	Seldom RE curtailments + multiple operations are cost advantageous, regulatory authorities need to be sensitized for ESS utilization opportunities
Pietila et al. (2012)	n.c.	Zero peak residential with PV-Battery systems	Control, efficiency, architectural and user behaviour measurements can eliminate 50% of on-peak consumption, smart PV-battery sizing brings great cost advantages

SOURCE: The author

Cited articles from the field of business models and applications, relevant for distributed battery systems, including information about the importance of electricity market regulations and politics, are summarized TABLE 17.

TABLE 17: LITERATURE ABOUT BATTERY TECHNOLOGY AND APPLICATION SUMMARY

Source	Topic	Main results or information
Higgins et al. (2014)	Influences of **electricity tariff** structures on residential PV-battery systems for peak demand services	20% load shift with battery system have positive cost impact for consumer. Overall positive effect for electricity system by demand flattening
Paine; Homans, Frances R.; et al. (2014)	Influence of **market rules** on ESS characteristics, applications and profitability	Different pricing concepts decide on viability of ESS
Behrangrad (2015)	ESS **business models** for demand side management (DSM)	Method for development of business models for DSM which can be adapted for ESSs
Anuta et al. (2014)	Impact of **regulatory** and electricity market structures on ESSs	Creation of separate asset class for ESS, standardised integration and operation procedures, support multiple utilization, updating market for ancillary service energy requirements
Poudineh; Jamasb (2014)	Network **investment deferrals** by active Network Operators, contracting multiple flexible demand utilities	ESS for grid investment deferral by active network operators, doing demand driven investment show more cost-efficient solutions
Battke; Schmidt (2015)	**Demand-pull policies** for ESS integration	Supporting ESS as multipurpose utilities, starting with the most profitable applications to introduce technology to the market with controllable costs.
Taylor et al. (2013)	Finding of **pathways** for ESS	Presents a method to identify pathways for ESS market introduction
Jingwei Zhu, Michael Z. Q. Chen, Baozhu Du (2014)	**Pricing Scheme** for ESS integration	Method for ESS integration only based on electricity prizes

SOURCE: The author

Current battery technologies and applications

Poullikkas (2013) identified lead-acid, lithium-ion, nickel-cadmium, sodium-sulfur and vanadium redox flow and zinc-bromine flow batteries as main technologies for current operational large-scale energy storage applications. Largest operational systems are sodium-sulfur based and smallest are vanadium-redox flow. Main applications are ancillary services like integration of renewable energy generation to existing power systems in terms of grid stabilization, impact smoothening and frequency control.

Ferreira Lopes et al. (2013) published an overview of different ESS applications and technologies, based on a techno-economic literature research and indicates most appropriate combinations, which are in terms of batteries: Lead Acid, Ni-Cd and flow batteries for bulk storage, Lead-acid, NaS, Ni-Cd, flow and metal air batteries for distributed storage and lead-acid, NaS, Li-ion, NiMH and Zebra batteries for power quality applications. Nevertheless, under current insufficient remuneration of ancillary services large investments on ESSs are seen as not attractive.

Kear et al. (2011) presents a summary of commercialization process for Vanadium Redox Flow (VRF) battery systems, which are mainly operated in intermediate and large-scale utilization, working for the applications:

- Electricity grid load levelling,
- Utility-scale renewable electricity generation,
- Distributed-energy/remote-area power supply

Cost estimations indicate still higher cost for batteries compared to conventional generations, based on fossil fuels. Nevertheless Kear et al. mention that on the long term subsidies of renewable energies together with storage could be self-payed by avoidance of environmental extranalties.

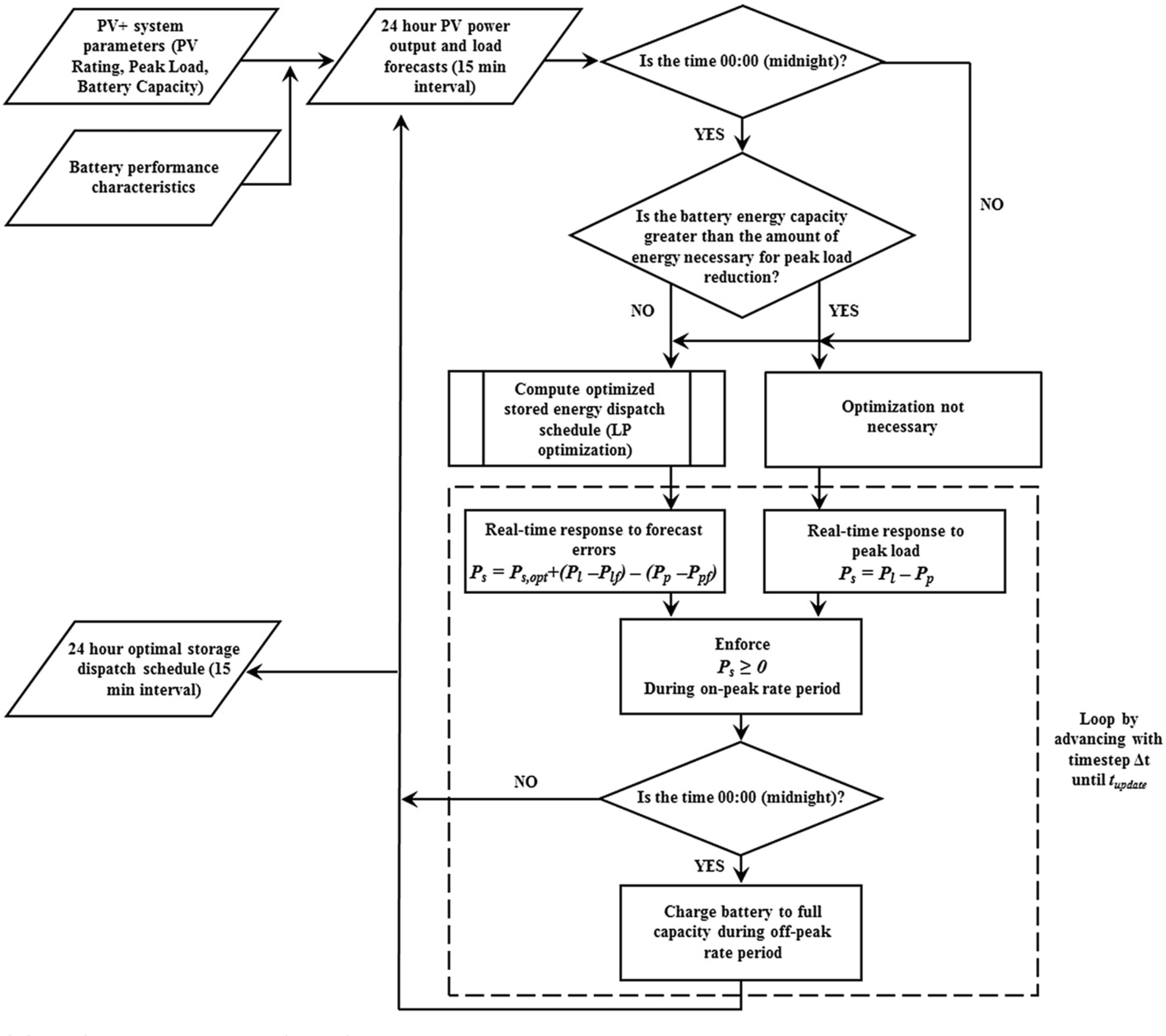
Arbitrage operation

Bradbury et al. (2014) simulate the economic performance in arbitrage application for 14 types of electrical ESS technologies, using 2008 US American electricity prices with the linear optimization aim of achieving a 10 % internal rate of return (IRR). The battery technologies considered are lead acid, Nickel Cadmium, lithium-ion, sodium/nickel chloride (ZEBRA), sodium sulfur (NaS), vanadium redox flow (VRF) and zinc bromide (ZnBr) and all techno economic data are taken from literature. The optimal capacity of energy storage for batteries is at 4 or less hours, whereby results differ considerable depending on applied real-time market prices. Lead Acid and ZEBRA batteries are the only once reaching positive IRR, whereby ZEBRA batteries show results comparable to these of mature technologies such as PHS and CAES.

Dispatch for on-grid PV-battery systems

Nottrott et al. (2013) model optimal energy dispatch schedules for peak net load management and demand charge minimization for on-grid combined photovoltaic and lithium-ion battery storage systems, utilizing consumer load and PV generation forecasts and based on 2011 US American market prices. Systems working with forecast data show increase cost performance compared to fixed on-/off-peak dispatching and positive net present values for installation cost beginning in the range of 450 $/kWh, based on a battery lifetime of 3000 cycles at 80 % depth of discharge (DoD). The used optimization process criteria and algorithm are illustrated in FIGURE 24.

FIGURE 24: FLOWCHART ILLUSTRATING OPTIMIZATION AND OPERATION PROCESS



SOURCE: Nottrott et al. (2013)

ESS under grid capacity limitations

Manchester et al. (2013) studies the utilization of ESS at endpoint of electricity distribution grid to enable multiple renewable generation sources integration with maximum total power output exceeding feed in limitations. The combination of a 0.9 MW wind energy converter (WEC) and a 0.5 MW in-stream tidal energy converter (TEC) together with an ESS is simulated under limitation of 0.9 MW maximal electricity feed in. Due to framework conditions this application is characterised by a storage system with maximum charge rate of 0.5 MW, maximal discharge rate of 0.9 MW and operation strategy that strives for discharging whenever possible to free storage capacity for future excess renewable generation. Without ESS maximal feed in restrictions would curtail down the TEC electricity sells by 8.7 %. Under consideration of an ESS with a total efficiency of around 64 % a respective of 5.6 % more energy can be sold, what results in a simple payback of 35 years, assuming a capacity of 6.8 MWh and absolute installation costs per capacity of 250 $/kWh. Nevertheless two reasons to install the ESS are given by Manchester et al. (2013), policy limitations which only allow excel renewable generation resource installation in combination with an ESS or economical advantageous dimensioning of ESS in combination with minor renewable generation curtailments. An ESS with a capacity of only 1 MWh (15 % of required to avoid curtailment) allow the sale of 54 % of excess production and has a simple payback of 9.3 years.

Application specific observations concerning ESS:

- High, short term ESS discharging rates lead to lower capacity requirements
- Self-discharge plays a minor roll due to short storage periods
- Hundreds of small cycles and few deep cycles are necessary and show similar participation in total energy throughput
- Diseconomies of scale characteristics

Rural electrification PV and ESS

Carrasco et al. (2014) presents the experiences made within a sample of 41 solar home systems containing photovoltaic and/or lead acid battery systems as a part of a rural electrification programme installing over 13,000 systems of in Morocco. Failures of system components are analysed, in especial of the lead acid batteries representing the most costly and critical one whereas PV modules showed a reliability of 99.85 % and maximum power degradation rates of 6.7 % with standard deviation of 2.0 % after 6.15 years of operation. Capacity deterioration of the 150 Ah C_{20}, at 20 °C lead acid batteries, used with 30-50 % DOD rates, representing a 5 days autonomy, show 40 % average capacity loss over 18 months of operation. Useable capacity of 80 % of the nominal, internationally indicated as end of life, is reached after about one year of use, but experienced, user motivated, battery change happened only after 5.5 years, when frequent blackouts occurred, what is below 20 %. Main reasons for battery degradation rates are likely to be low manufacturing quality, difficult behaviour prediction of degraded batteries and charge controllers allows DOD close to 100 %.

ESS in Micro Grids

Tan et al. (2013) represents energy storage system (ESS) as the fundamental element of micro grids (MG) and represents a techno-economic comparison of different ESS technologies for MG applications.

Tan et al. (2013) indicates main benefits of ESS utilization in utility grids referring to DOE (2010) and in MGs, as shown in TABLE 18.

TABLE 18: MAIN BENEFITS OF ESS UTILIZATION IN UTILITY- AND MICRO GRID

Benefits of ESS utilized in utility grid	Benefits of ESS utilized in MG
Short term power supply	Area and frequency regulation
Facilitating integration of RES	Renewables grid integration
Arbitrage	T&D upgrade deferral and substitution
Optimization of micro source in MG	Load following
Power quality improvement Primary	Electric energy time shift
	Ancillary services

SOURCE: Adapted from Tan et al. (2013)

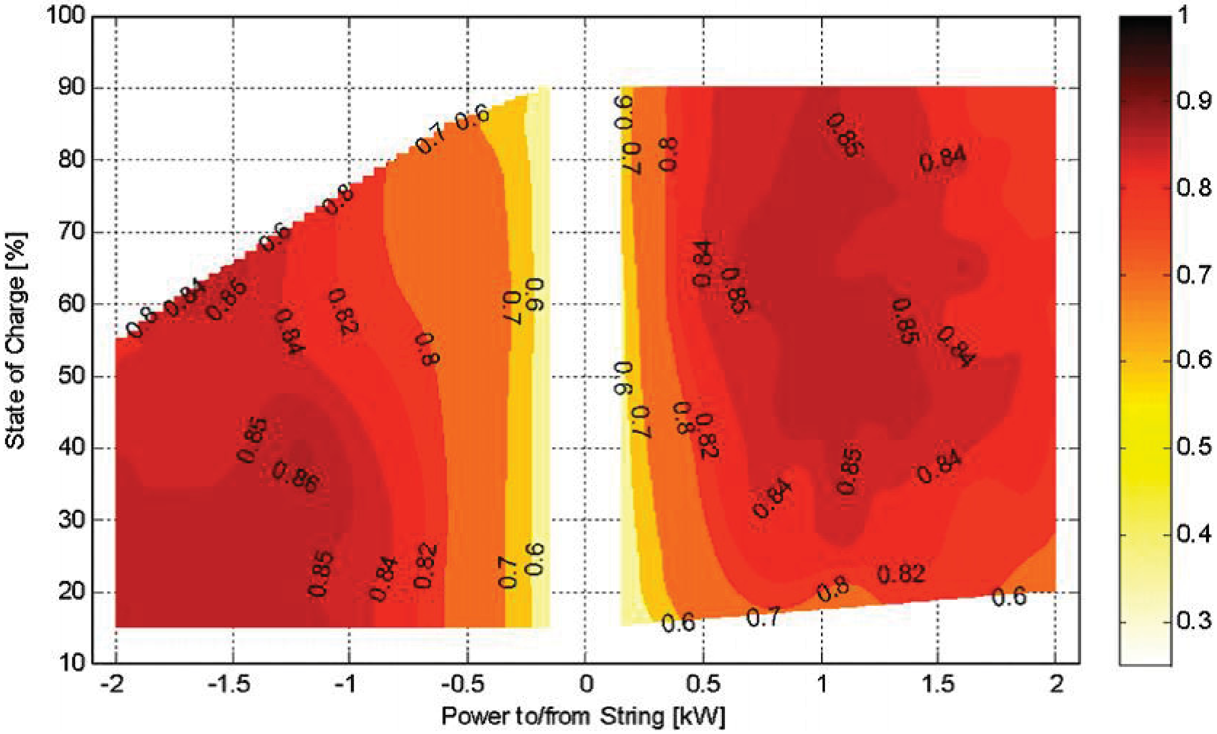
Most relevant simulation software and tools indicated in this article include ES-Select, PLATOS Hybrid2, Homer, IPSYS and MATLAB/Simulink. Referred to a techno-economic analysis carried out by Garimella and Nair (2009), NiMH batteries showed best characteristics in terms of power output, voltage profile and charge–discharge characteristics. Lead-acid battery showed the lowest costs for renewable energy (RE) applications compared to Nickel–Cadmium (NiCd), Nickel–Metal Hydride (NiMH) and Li-ion batteries, which were indicated as most appropriate for applications with low duty cycles. Sodium-sulfur (NaS) batteries are indicated to show high energy density, high power, good cycle and calendric life, but due to technical characteristics mora appropriate for larger shale applications.

In general costs of current technologies are indicated as being still too high for grid scale ESS integration.

VRV battery system in large scale applications

Turker et al. (2013) presents an analysis of vanadium redox flow battery efficiency in relation to state of charge (SOC) and power values as measured with a kilowatt scale *CellCube FB 10/100* commercial VRFB unit manufactured by Cellstrom GmbH. System efficiency is indicated to vary dependent on electrochemical conversion energy losses and auxiliary power consumptions for pumping, which are decisive at very low power levels. FIGURE 25 shows the efficiency of a VRF string in dependence on SOC and dis-/charging power.

FIGURE 25: EFFICIENCY OF A VRF STRING IN RELATION TO SOC AND POWER



SOURCE: Turker et al. (2013)

String efficiency is highest at low SOC and high power during charging and medium to high SOC and medium power during discharging.

High and low SOC combined with high power level lead to lowest voltage efficiency values, explained in detail by Sukkar and Skyllas-kazacos (2003), whereby increasing power in general effects decreasing efficiency caused by overvoltage losses. Pumping power for charging is higher than discharging, with values increasing with SOC and power during charging or increasing SOC and increasing power for discharging respectively.

Life cycle cost of ESS in stationary applications

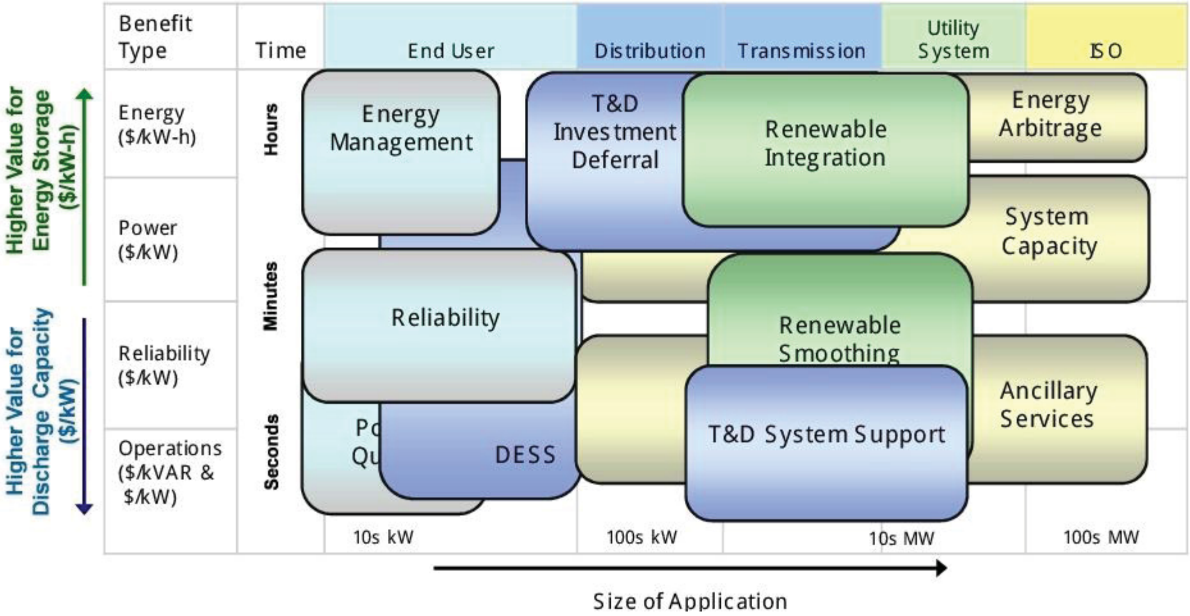
Battke et al. (2013) reviews life cycle costs of batteries in stationary applications with focus on lead-acid, lithium-ion, sodium–sulfur and vanadium redox flow batteries. Generally, in the storage debate, technologies and applications are classified in the two criteria: power [P] (up to 30 min of discharge duration) and energy [E] (above 30 min).

The article focuses on six storage applications, based on actual and promising future relevance due to renewable energy source integration, which are:

- Utility Energy Time-shift, [E],
- ○ (100 MW / 8 h/ 1 cycle per day)
- Energy Management (community scale), [E],
- ○ (10 MW / 5 h / 0.68 cycles per day)
- Transmission & Distribution (T&D) Investment Deferral, [E],
- ○ (0.1 MW / 2.5 h / 2 cycles per day)
- Increase of Self-consumption, [E],
- ○ (2.5 kW / 4 h / 0.6 cycles per day)
- Area and Frequency Regulation, [P],
- ○ (2 MW / 0.25 h / 34 cycles per day - DOD 5 % each)
- Support of Voltage Regulation, [P].
- ○ (1 MW / 0.25 h / 0.68 cycles per day)

Lifecycle costs for all battery types and applications are calculated, whereby sodium-sulfur batteries show lowest average costs in the four Energy applications (0.18, 0.27, 0.17 and 0.36 €/kWh) and lithium-ion batteries for the two power applications (0.80 and 0.98 €/kWh). Nevertheless the enormous uncertainty ranges of the mean lifecycle costs of each technology are still superior compared differences between technologies. Battke et al. (2013) also presents also a structuring scheme for energy storage applications, as published by EPRI and Raster (2010), who is mapping a framework to bundle benefits by application, as shown in FIGURE 26.

FIGURE 26: FRAMEWORK TO BUNDLE BENEFITS BY APPLICATION



SOURCE: EPRI; Raster (2010)

Degradation rates of ESS with wind turbines

Krieger et al. (2013) presented a comparison of degradation rates and mechanisms in lead acid, LCO (lithium cobalt oxide), LCO-NMC (LCO-lithium nickel manganese cobalt oxide composite) and LFP (lithium iron phosphate) batteries in off-grid application, when charged by wind turbines with maximal C-rate of 0.8. Pulse charging contributes to incomplete charging and variable charge results in greater partial charging, both turned out to lead to rapid degradation of lead-acid cells due to apparent high rates of sulphation and resistance growth. LCO batteries are less sensitive to variable charge with greater partial charging results without impact on capacity fade. LCO-NMC cells show a superior overall performance, with slower degradation under variable and so incomplete charging due to limited side reactions at high state of charge. LFP batteries show little sensibility on variable and short pulse charging, no increase in resistance, a longer life time, deep discharge and flat voltage curves and are therefore identified as most suitable, studied alternative for pulse charge situations.

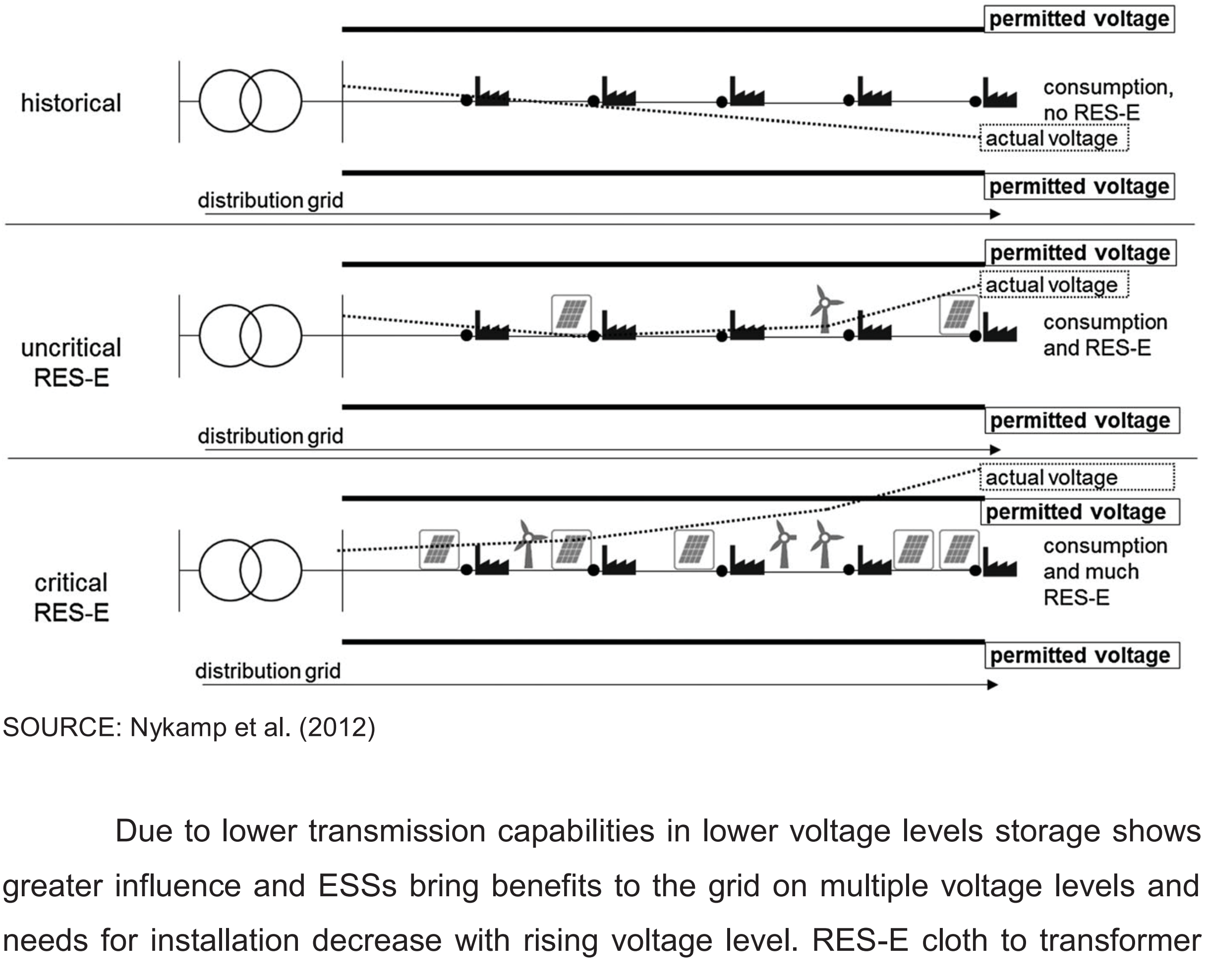
Break-even point for storage PV in power distribution grids

Nykamp et al. (2014) presents an approach for calculation of the break-even point (BEP) for ESSs substituting distribution grid (DG) reinforcements and of ESS benefits for upstream grid levels in networks with increasing fluctuating, renewable generators. Some benefits of ESS in the DG due to compensation of renewable generation peaks are the avoidance of

- upstream transformation to higher voltage level,
- grid reinforcement due to frequency and voltage rise and
- transnational power transfers.

Whereby transformation or reinforcement of voltage level represents relocation of existing problem to higher voltage level and may cause further activities. FIGURE 27 illustrates some voltage situations occurring in distribution grids and the impact of renewable energy sources (RES-E).

FIGURE 27: VOLTAGE SITUATIONS IN DISTRIBUTION GRIDS WITH RENEWABLE ENERGY GENERATION SOURCES

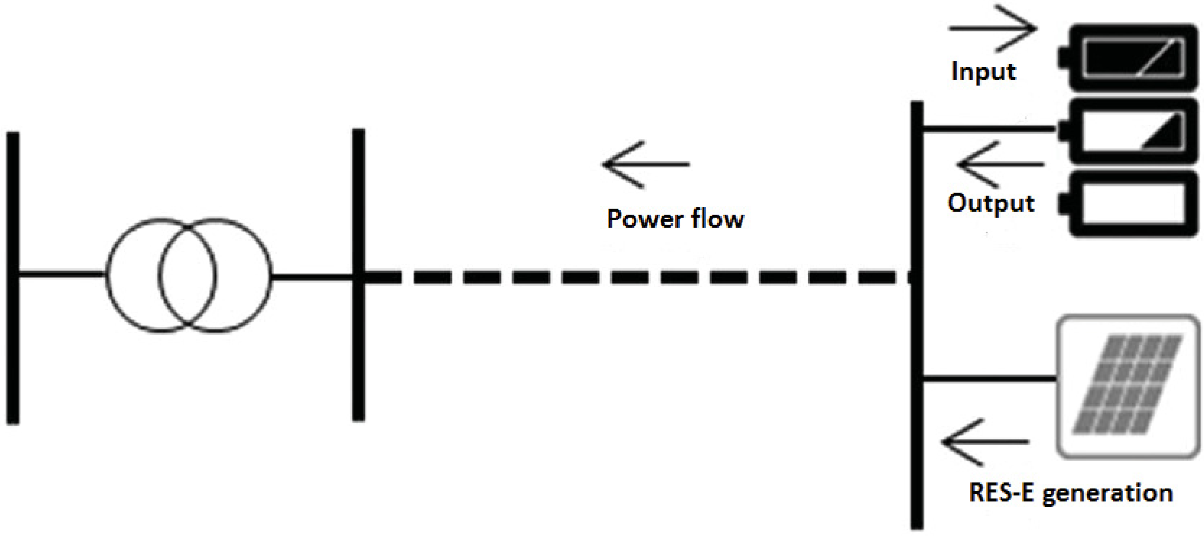


SOURCE: Nykamp et al. (2012)

Due to lower transmission capabilities in lower voltage levels storage shows greater influence and ESSs bring benefits to the grid on multiple voltage levels and needs for installation decrease with rising voltage level. RES-E cloth to transformer points to higher voltage levels show less impact on local voltage disturbance but still on higher ones. The BEP between conventional reinforcement and ESS integration is calculated by setting the sum of operational expenditures (OPEX) such as maintenance and losses, and capital expenditures (CAPEX), such as Interest and

Depreciation, for each solution. The system arrangement is shown in FIGURE 28 and the considered application for cost calculations is peak shaving, whereby the ESS gets charged whenever power flow leads to violation of permitted network limitations and discharges immediate to enable following utilization.

FIGURE 28: SYSTEM STRUCTURE AND ENERGY FLOW SCHEME



SOURCE: Nykamp et al. (2012)

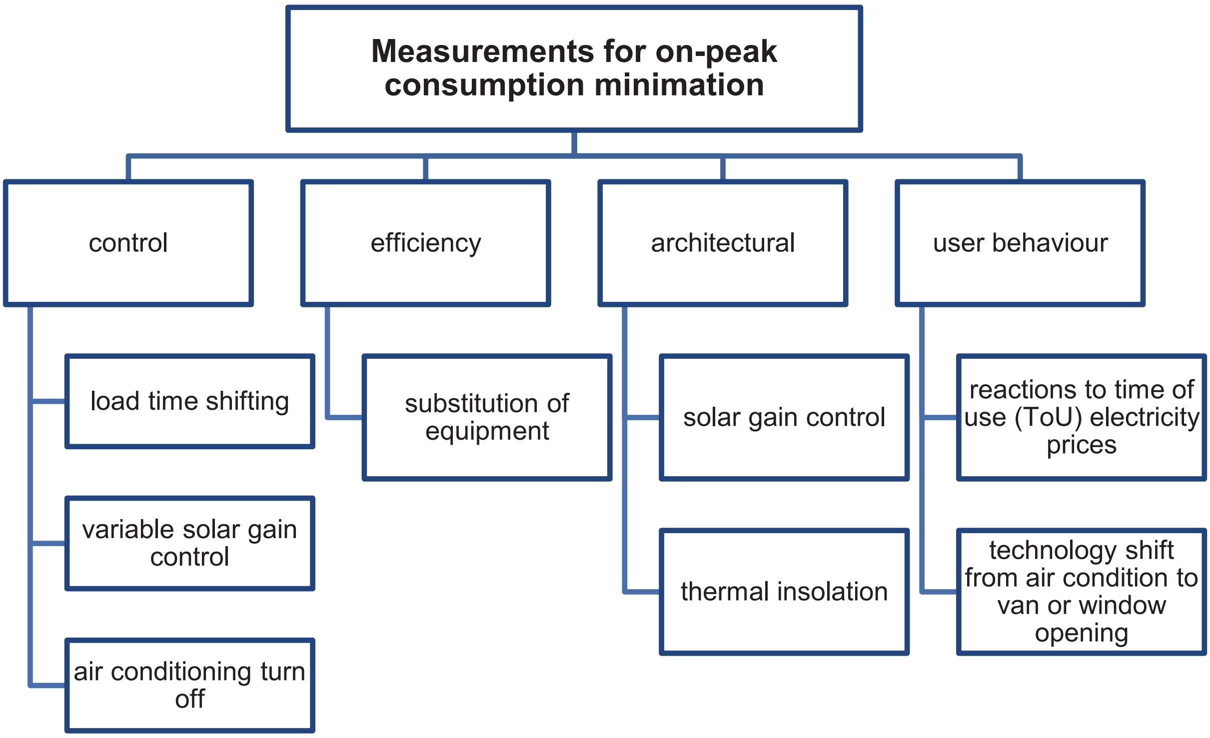
BEP calculations as cost per storage capacity [$/kWh] need to be adjusted for specific situations, depending on cost driving parameters such as grid reinforcement distances, area costs depending on location characteristics and impacts on upstream grid levels for the traditional solutions on the one side and required storage capacity, techno economic ESS characteristics on the other side. Some cost relevant observations on ESS are made, which are:

- Acceptance of little (high and seldom) curtailments of renewable energy generation leads to disproportional great reductions of required storage capacities
- PV peak shaving applications need high capacities, show low utilization rates and therefore a multiobjective operation of ESS improve profitability and promote more efficient technologies
- Regulatory authorities need to be sensitized to storage options as an alternative to grid reinforcement to guarantee stimulation for cheapest investment solution

Houses without grid demand during on-peak hours using PV-battery systems

Pietila et al. (2012) studied the possibility of residential buildings without electricity consumptions from grid during on-peak hours, based on data of a tract-built design in Toronto, Ontario, Canada. Two main observations have been made. First, until half of the on-peak consumption can be eliminated by measurements shown in FIGURE 29.

FIGURE 29: MEASUREMENTS FOR



SOURCE: Pietila et al. (2012)

To eliminate the remaining on peak load, three PV and ESS systems were analysed. A PV only and a PV and Battery system to shift the total on peak demand and a PV and battery system with less rigid requirements, reduced to a curtailment of the 10 hottest and therefore most critical days.

The studies are only searching for technical feasibility and do not consider system costs, but results show that the less rigid requirements lead to PV and battery system capacity halving. This indicates huge potentials for cost reduction by smart sizing of the PV-battery systems.

3.2.2 Business Models and Market Structures for ESSs

Influences of electricity tariff structures on residential PV-battery systems for peak demand services

Higgins et al. (2014) simulated the utilization of residential PV with battery systems in combination with a scenario of six different electricity price tariffs based on critical-peak pricing (CPP), time-of-use (ToU) and flat-pricing structures to avoid peak demands as shown in TABLE 19.

TABLE 19: PV-BATTERY SYSTEM AND CONSUMER CHARACTERISTICS FOR SIMULATION

System number	Battery capacity [kWh]	PV power [kWp]	Consumer type			
			Detached house huge	Detached house small	Semi-detached house	Apartment
S1	No	1.5	X	X	X	
S2	No	3.5	X			
S3	No	5.5	X			
S4	2	No	X	X	X	X
S5	2	1.5	X	X	X	
S6	8	3.5	X			
S7	16	5.5	X			
S8 (off-gird)	24	5.5	X			
S9	No	No	X	X	X	X

SOURCE: Higgins et al. (2014)

The different electricity tariff options are presented in TABLE 20 and consist of daily and/or consumption dependent charges. Tariffs are designed to keep constant total electricity bills for customer types if no consumer behaviour occurs.

TABLE 20: ELECTRICITY TARIFF OPTIONS FOR SIMULATIONS

Electricity tariff	Characteristics	Fixed charge [A$]	Flexible charge [A$]
Base	Flat daily charge + flat energy charge	0.55 [A$/day]	0.28
T1	Higher flat daily charge + lower flat energy charge	4.20	0.14
T2	Peak based daily charge + flat energy charge	0.85 [A$/kW$_{\text{(max. daily load)/day}}$]	0.14
T3	Peak based daily charge + ToU energy charge	0.85 [A$/kW$_{\text{(max. daily load)/day}}$]	0.11 (10pm-7am); 0.13 (8am-4pm and 8-10pm); 0.34 (4pm-8pm)
T4	Peak based daily charge + CPP energy charge	0.85 [A$/kW$_{\text{(max. daily load)/day}}$]	0.16
T5	Peak time dependent fixed charge. Monthly peak time inside/outside 4 pm – 9 pm	3/0.3 [A$/kW$_{\text{(max. monthly load)/day}}$]	0.10

SOURCE: Higgins et al. (2014)

Different system purchase prices with consideration of future cost reductions are taken for all simulations.

Based on this data, simulations showed positive impact on consumer electricity costs by load shift of about 20 % under CPP and ToU tariffs during on peak time, using PV-battery systems and thereby helping the electricity provider flattening demand curves. Main message of Higgins et al. (2014) is the positive effect on electricity system and consumer electricity bill, PV-battery systems can provide under implementation of favouring tariff structures.

Influence of market rules on ESS characteristics, applications and profitability

Paine et al. (2014) stresses on the importance of market rules for ESS operational strategies and profitability, simulating an exemplary storage facility under independent system operators (ISO) market rules from Midcontinent ISO (MISO) and ISO-New England (ISO-NE) from the year 2011. ISOs calculate electricity prices for different market nodes depending on the location, using the location marginal pricing (LMP) approach and taking into account markets for grid stability services, such as spinning reserves and frequency regulation. Paine et al. (2014) name three influences on the value of ESSs, which are:

- the way, electricity market functions,
- validation of ESS for the sale of electricity,
- way of participation and making money with regulation services.

The differences of frequency regulation compensation for ESSs in the two different ISOs are compared in TABLE 21.

TABLE 21: COMPARISON OF MARKET RULES FOR FREQUENCY REGULATION SET BY ISOS

Frequency regulation	MISO	ISO-NE
payments	capacity Positive control (injection)	capacity positive and negative control
charges	Negative control (load)	

SOURCE: Paine; Homans, Frances R; et al. (2014)

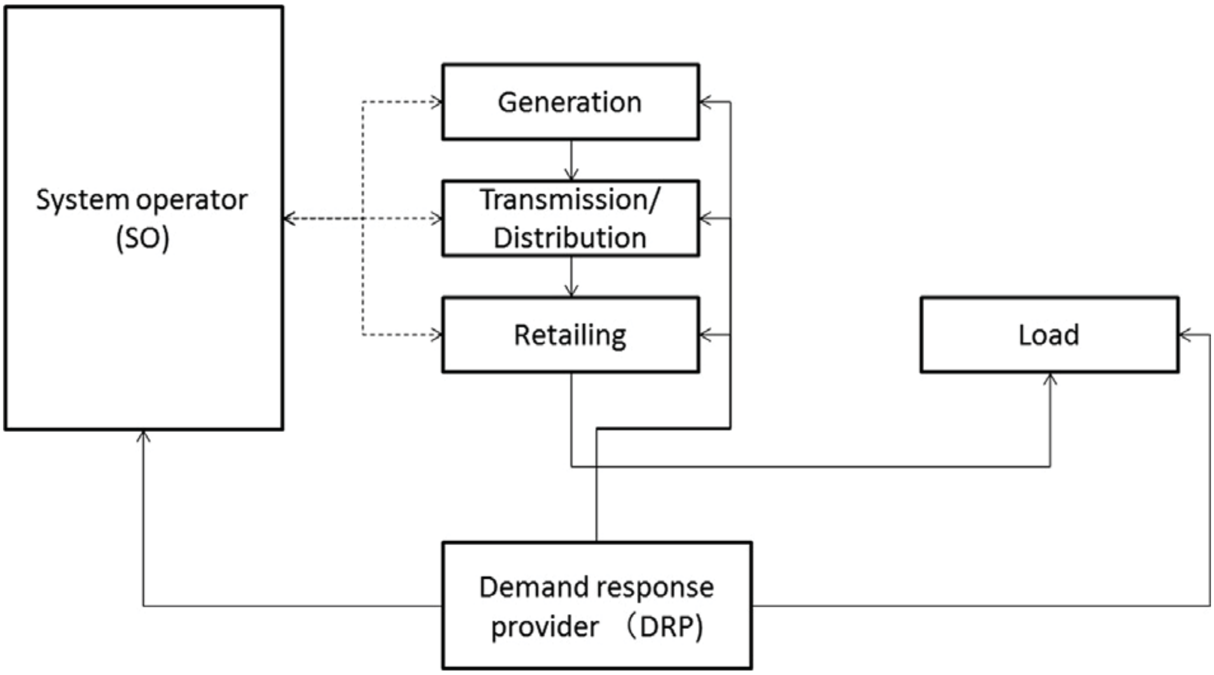
Using a discrete state dynamic programming model, historic electricity prices and 2011 ISO market regulations in MISO and ISO-NE, the operation of a pumped hydro storage facility acting as a frequency service provider was analysed and differences in revenues compared. Total operating profit variations of over 100 % and even over 800 % for frequency regulation revenue ware observed at the same pricing node. As a final remark Paine et al. (2014) alert that profit-maximizing developers may not select ESS based on actual market needs but yes on profit-orientated criteria such as market rules.

ESS business models approach, abstracted from demand side management

Behrangrad (2015) reviews business models for demand side management (DSM) in the electricity market. This business models are strongly related to factors such as power system characteristics, infrastructure, electricity market regulations and mechanisms. The article classified DSM activities into energy efficiency (EE) and demand response (DR) and lists demand response providers (DRP) as DR aggregator, energy serving companies (ESCO), load-curtailing entity, load curtailment provider, or load owner where. In this context energy storage systems can be interpreted as DRP and therefore method and results can be transferred to identify also new ways of EESS utilisation.

FIGURE 30 illustrates the constitution of typical electricity market segments, considered as stakeholders for demand response activities to achieve economical optimization.

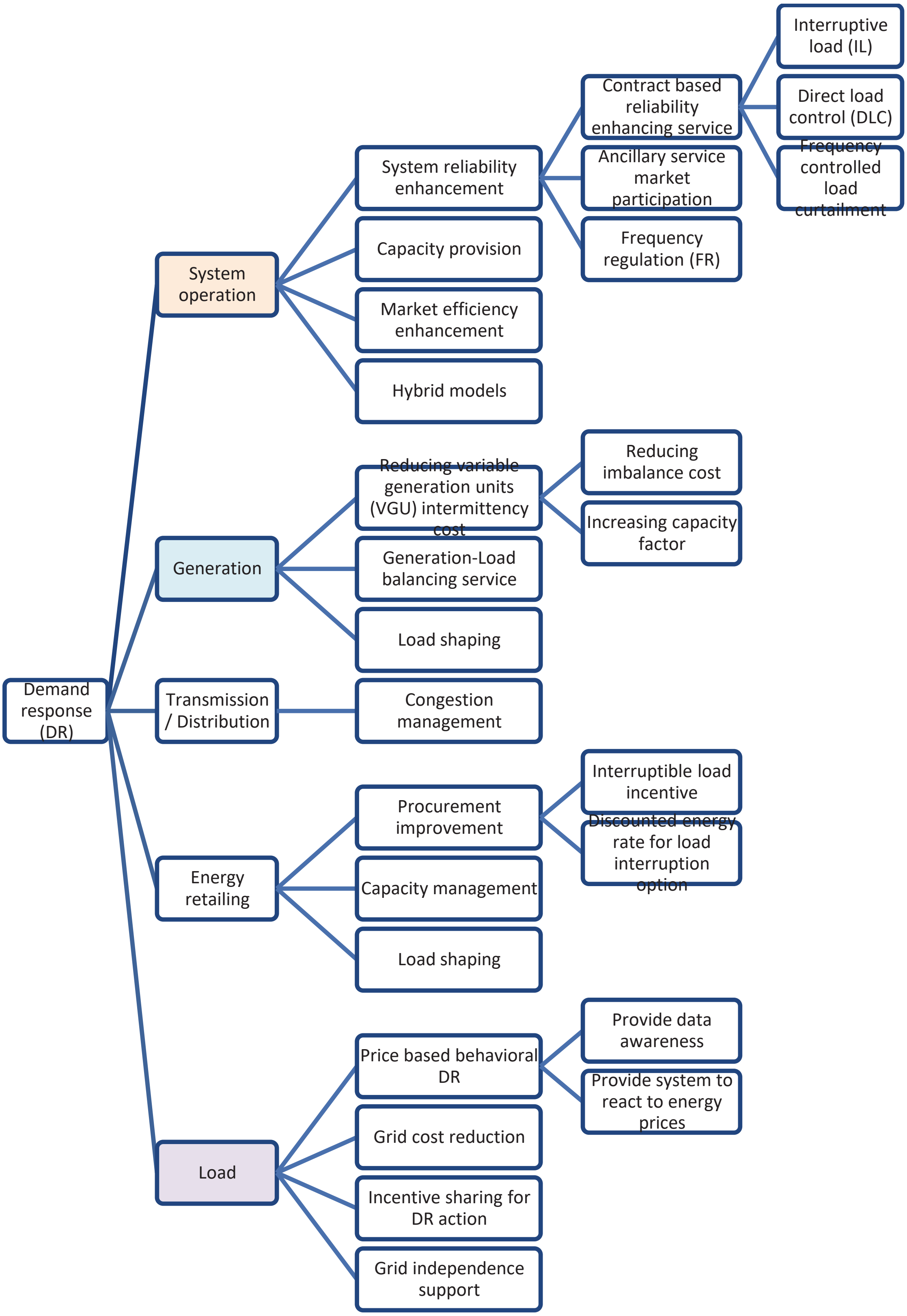
FIGURE 30: DEMAND RESOURCE PROVIDER (DRP) AND ENERGY MARKET SEGMENTS



SOURCE: Behrangrad (2015)

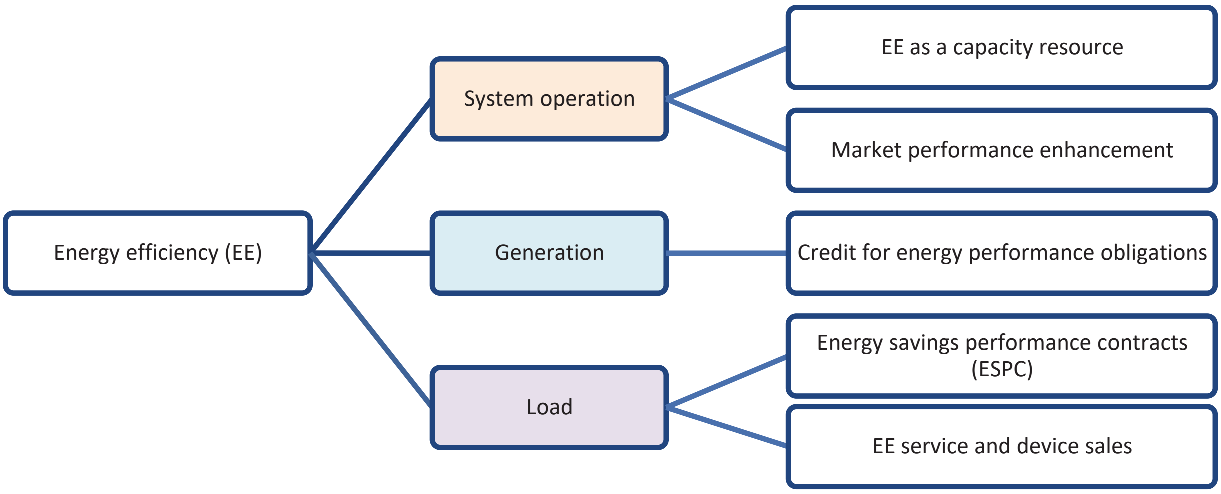
To analyse the different business models, Behrangrad uses the structure as shown in FIGURE 31 and FIGURE 32, whereby further external parameters, such as market structure, generation and transmission network capacity and electricity tariff structure are not represented in the figures but anyways relevant.

FIGURE 31: DRP BUSINESS MODELS BASED ON DR



SOURCE: Adapted from Behrangrad (2015)

FIGURE 32: DRP BUSINESS MODELS ON EE BASIS



SOURCE: Adapted from Behrangrad (2015)

Beside listing different approaches of business models for DRP, Behrangrad (2015) also shows relevant characteristics to define and evaluate them, compare TABLE 22:

TABLE 22: CHARACTERISTICS OF BUSINESS MODELS

DSM transaction characteristics	Renewable energy (RE) correlation	DSM load control characteristics
DRP offered value Value for purchaser Primary transaction driver Activation trigger		Response speed Response duration Advance notice Location sensitivity Actual usage rate

SOURCE: Adapted from Behrangrad (2015)

Behrangrad (2015) states also, that even so business models are treated separately, DR activities and this way also the business model characteristics can be combined in different ways.

Impact of regulatory and electricity market structures on ESSs

Anuta et al. (2014) is a review of the implications of regulatory and electricity market structures on ESSs on grid scale.

Based on an analysis of regulatory changes in countries which have high renewable targets and current planes of ESS deployments, three major problems for undertaking multiple EES system implementations where identified:

- low electricity market liquidity,
- changing market conditions;
- lack of common standards and procedures for evaluating, connecting, operating and maintaining ESS.

Recommendations for changes or creation of policies, regulation and market arrangement are made. Regulatory and policy recommendations in alignment of renewable policies to ESSs:

- creating a separate asset class for ESS,
- associated rules for regulated and competitive operations,
- standardising assessment frameworks, connection and operational procedures for the use of ESS.

Three main electricity market recommendations where formed, which are:

- updating rules to support simultaneous ESS operation across wholesale, ancillary services and capacity markets,
- updating market rules to allow compensation for flexible and highly accurate responsive demand and generation technologies (ESS),
- updating market ancillary service energy requirements.

Anuta et al. (2014) names several parameters, which influence and define the creation and selection of business models for ESS utilization. These parameters include: Owner types for ESSs, as referred to Pomper (2011) and Vasconcelos et al. (2012), system location, regulatory framework, target service required on the location on the grid, benefits of ESS services, market and regulatory structures and the ESS service pricing model. An overview of some parameters of influence on form business models for ESSs is given in FIGURE 33.

FIGURE 33: PARAMETERS FOR ESS BUSINESS MODELS

SOURCE: Adapted from Anuta et al. (2014)

Most relevant applications for EESs and the involved stakeholders are listed in TABLE 23.

TABLE 23: APPLICATIONS AND STAKEHOLDERS FOR ESS

Application	Stakeholder involved
Blackstart	T&D
Power quality and harmonics	T&D
Reserves (spinning or non-spinning)	T&G
Governor/inertial response	T&G
Voltage regulation	T&D
Frequency regulation	T&G
Renewable smoothing dispatch and integration	T&D, Generator
Capacity management	T&D
Increased asset utilisation and reduced losses by load levelling	T&D, Generator
Peak shaving/energy arbitrage	T&D, Generator

SOURCE: Adapted from Anuta et al. (2014), based on ERPI; Raster (2010), Manz et al. (2011), Taylor et al. (2012) and Strbac (2008)

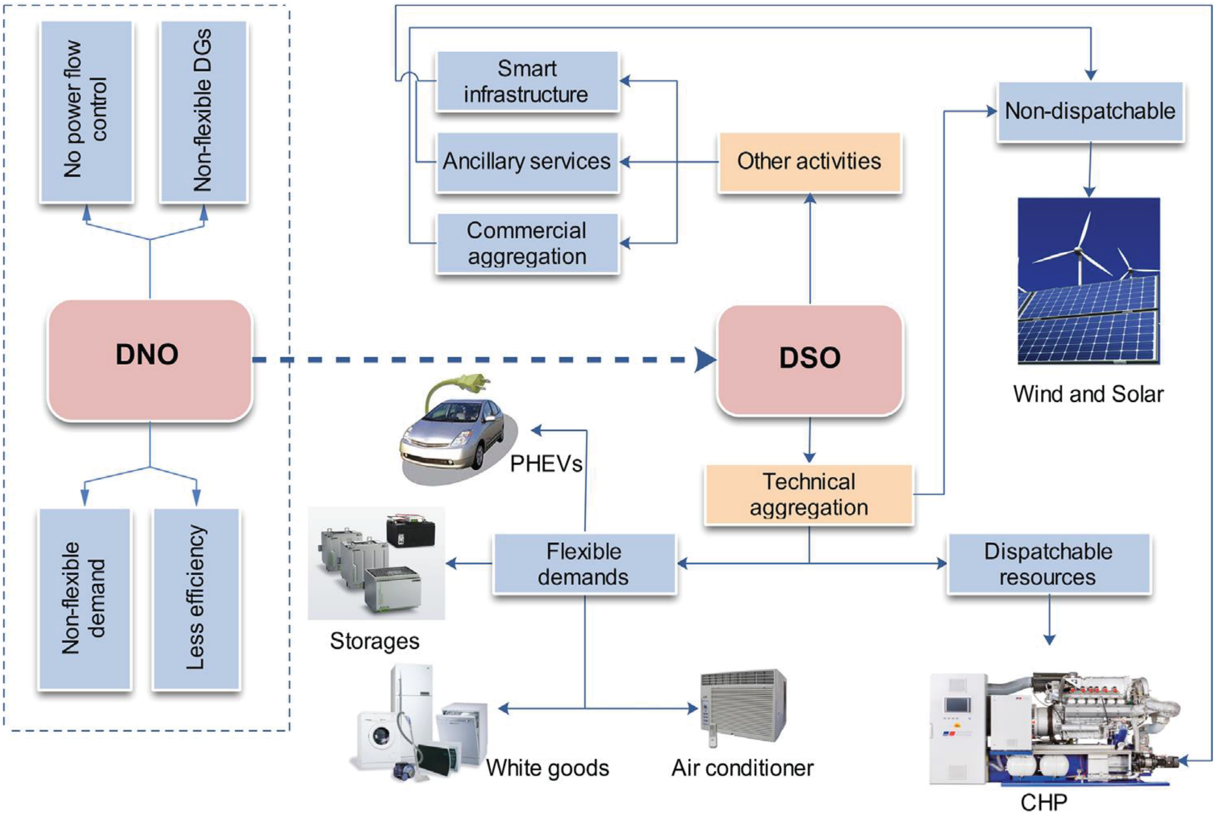
In general multifunctional utilization ESSs is recommended as the key goal to maximize benefits and realize cost effective ESS utilization. Respective changes in politics, regulations and market are essential actions to enable operators and customers to do so.

Network investment deferrals by active Network Operators, contracting multiple flexible demand utilities

Poudineh and Jamasb (2014) stress that step vice grid reinforcement by nature leads to over capacity until (if) demand finally reaches the expected value. Therefore, this paper discusses a new three stage market-based approach, as an extended business model, to define a economically efficient portfolio for demand driven investments under consideration of storage, distributed generation, demand response and energy efficiency to defer large scale network investment.

The extended business model proposed by Poudineh and Jamasb (2014) is based on the idea that Distribution System Operators (DSO) replace Distribution Network Operators (DNO) and are allowed to extend their commercial activities from connection- and use-of-system charges to interact with other market players, such as Consumer categories, Transmission System Operators (TSO), Distributed Generation (DG) Operators, Retail Suppliers. Grid reinforcement is an alternative to distributed generation and Storage on most economic target criteria as visualised in FIGURE 34.

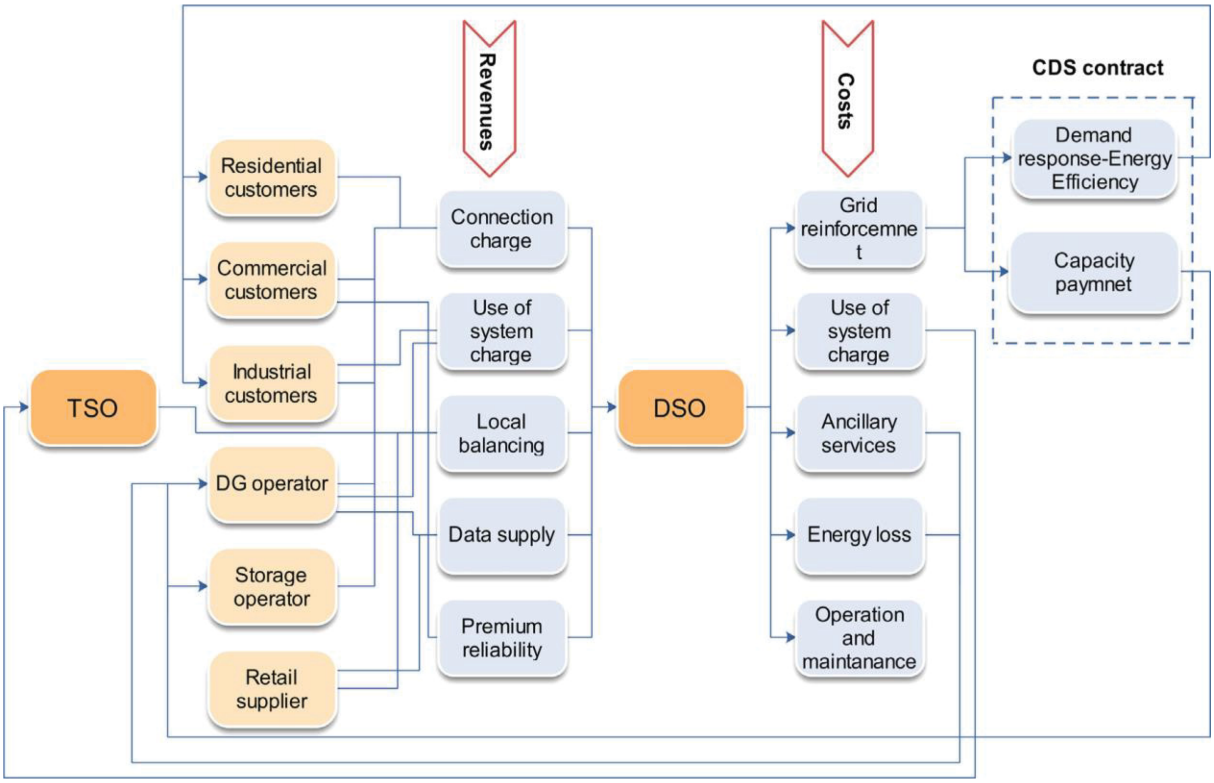
FIGURE 34: THE TRANSITION FROM DNO TO DSO MODEL



SOURCE: Poudineh; Jamasb (2014)

Further business activities can be undertaken, such as sell of premium reliability, data supply or local and national balancing. DSO contracts DG (and in this case also storage) operators on competitive basis with so called “contract for deferral scheme” (CDS) and pays them for providence of capacity. An overview of the extended business model for DSO is given in FIGURE 35.

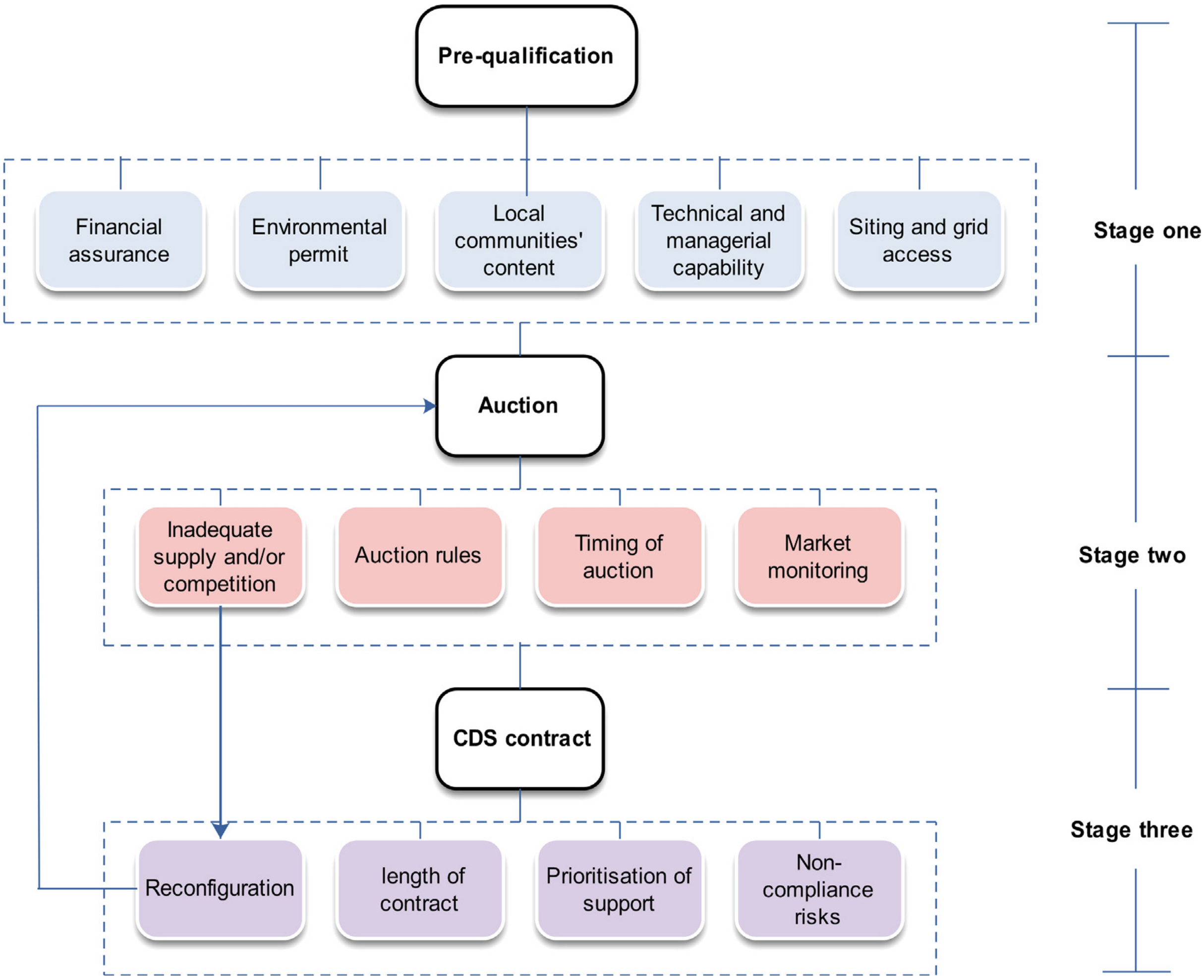
FIGURE 35: THE EXTENDED BUSINESS MODEL FOR DSO



SOURCE: Poudineh; Jamasb (2014), partially based on information in Van Werven; Scheepers (2005)

CDS is market based, all alternatives are treated equally, motivates investment in storage technologies, gives boost to integration of demand response and energy efficiency and is a mechanism for procuring on a non-discriminatory basis, a portfolio of capacity resources through a competitive forward auction process. The three steps of the CDS approach are: pre-auction, auction and post-auction, see FIGURE 36.

FIGURE 36: THE PROCEDURE OF CDS CONTRACT PROCUREMENT



SOURCE: Poudineh and Jamasb (2014), partially based on information in IRENA (2013)

The three steps are summarized below, in alignment with process and criteria shown in FIGURE 36.

1st step:

- DSO defines required capacities, locations and technical data for auction, based on an analysis of potentially network capacity shortages over the subsequent period. Resource suppliers are identified and evaluated in terms of reliability and an optional set of further pre-selection criteria, such as feasibility, institutional framework, regulations or technical condition of the power system. Approved suppliers are free to submit their bids to the auction.

2nd step:

- The auction can be of various designs, whereby descending clock auction is recommended due to the single buyer model character of the CDS contract acquisition and appropriate market characteristic, as noted in NYSERDA (2004). The open auction model with uniform pricing only identifies least cost suppliers due to price falling character and price as well as capacity committed are known.

3rd step:

- After nomination of service suppliers contracts are made and combined services delivered and payed. Simplified contracts are recommended to keep costs low, nevertheless some important points are recommended to find consideration, which are: Length of the contracted service, prioritisation of support in order to satisfy all related stakeholders, non-compliance risks and reconfiguration auctions due to unpredictable.

Poudineh and Jamasb (2014) conclude that the changings in electricity system constellations due to increasing distributed generation, demand side management and storage technologies lead also to new requirements for distribution networks and therefore request innovative solutions.

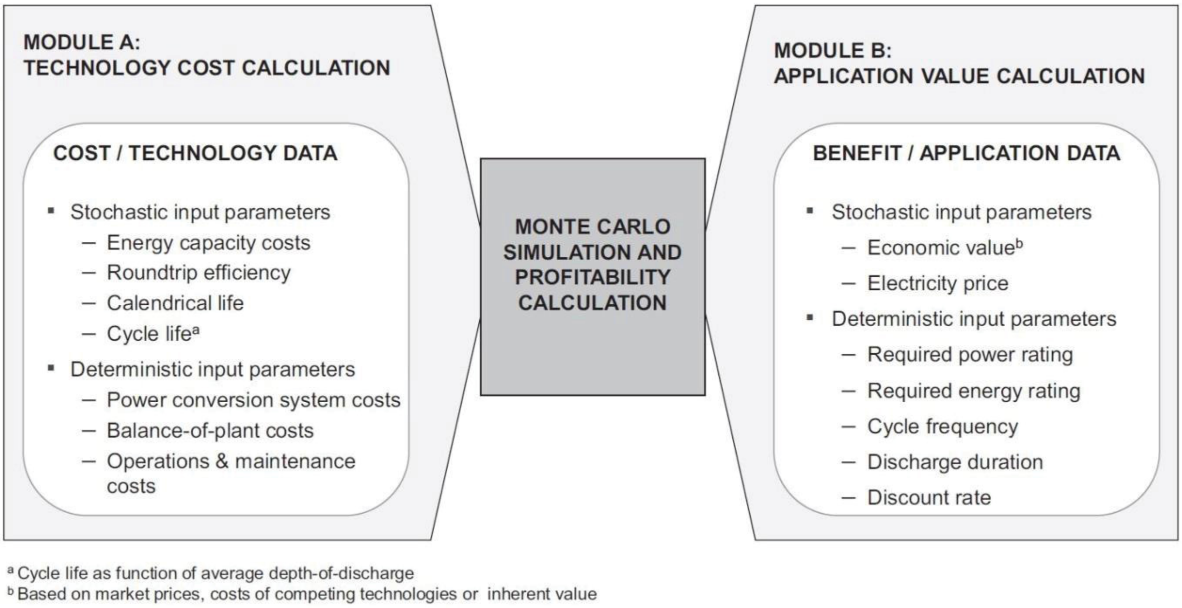
Demand-pull policies for ESS integration

Battke and Schmidt (2015) presents an approach of demand-pull policies (DPP) based on multiple use of stationary energy storage (SES) technologies on the example of a vanadium redox flow battery. Batteries can be understand as multi-purpose technologies, by definition of Wicklein (1998), being a technology with several distinct, economically relevant applications, which are primarily focused on one or also a few sectors, but still lacking of technological complementarities of general-purpose technologies. The author states that demand-pull policies can be used to stimulate the development and market introduction of cost intensive technologies but also can result in high subsidy payments like experienced in the German RES integration policies. Expenses for DPP can be limited by sequentially supporting applications based on their specific profitability gaps.

Based on a literature review, Battke and Schmidt (2015) claim that the economic framework of SES applications does not satisfy their multi-purpose character.

An exemplary analysis of a VRF battery in five selected SES applications shows different values for storage utilization, based on techno economic data input for the battery as well as for the value of service of applications, which are shown in FIGURE 37.

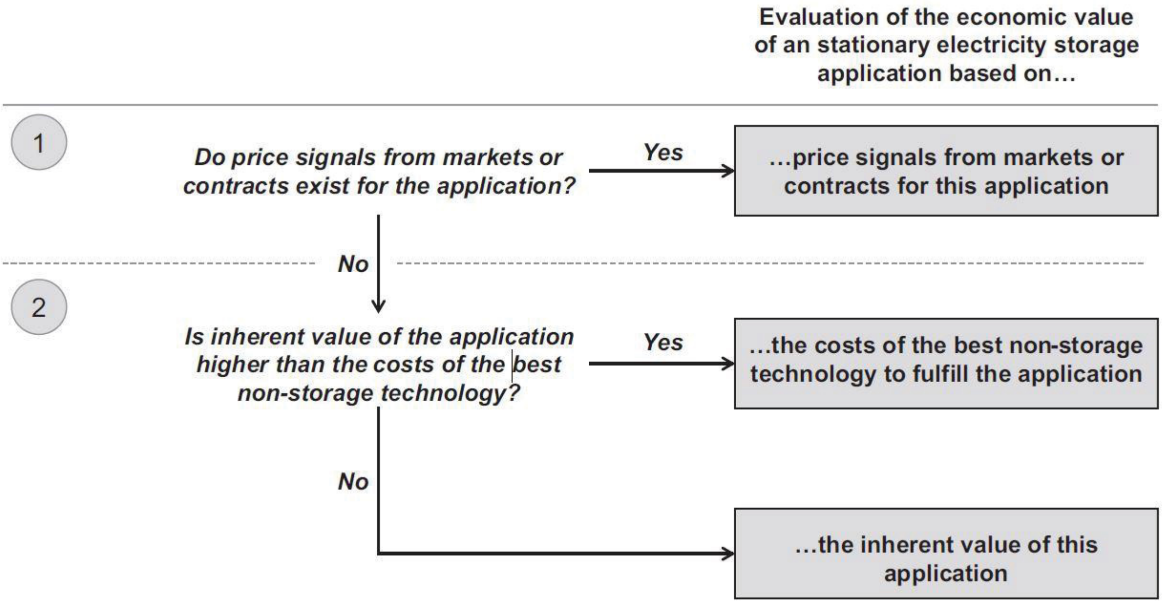
FIGURE 37: OVERVIEW OF METHODOLOGY AND INPUT DATA FOR PROFITABILITY ASSESSMENT



SOURCE: Battke and Schmidt (2015)

There is no standardized method for SES service value estimation. Possible approaches for calculation can be based on, flow chart presented in FIGURE 38.

FIGURE 38: SELECTION HEURISTIC FOR ECONOMIC VALUE CALCULATION OF SES APPLICATIONS



SOURCE: Battke and Schmidt (2015)

Even if the results are not direct comparable with previous studies, due to different methods, the economic ranking of applications shows similar results. Noting that profitability values and uncertainty vary significantly across applications and are all negative for VRF batteries. The results are listed from highest to lowest values for VRF batteries as follow:

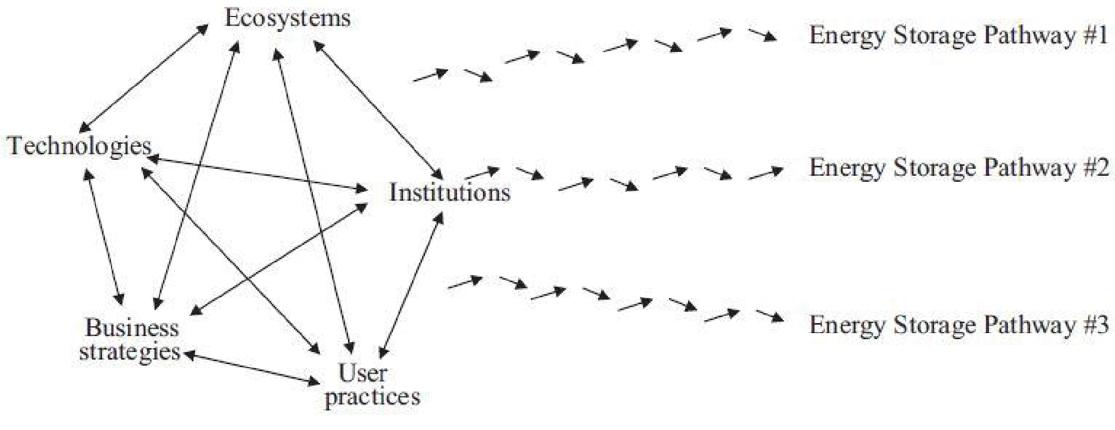
- Area & Frequency Regulation
- End-consumer Power Reliability
- Increase of Self-consumption
- Wholesale Arbitrage
- End-consumer Arbitrage

Based on this results Battke and Schmidt (2015) arguments that demand-pull policies for batteries as multi-purpose technologies can be a solution to support market entry and the relevance of stationary ESS service value analysis, based on its application, to identify the most appropriate one, promising the smallest costs of demand-pull policy.

Finding of pathways for ESS

Taylor et al. (2013) is presenting a method to develop three alternative pathways for energy storage, as shown in FIGURE 39, using a coevolutionary framework which considers changes in relevant dimensions of influence for ESS utilization.

FIGURE 39: COEVOLUTIONARY FRAMEWORK FOR ES



SOURCE: Taylor et al. (2013) extended from Foxon (2011) based on Norgaard (1994)

The five framework dimensions for ESS pathways, as defined by Foxon (2011), are defined and interpreted as:

- Technologies: *"methods and designs for transforming matter, energy and information from one state to another in pursuit of a goal or goals"* (p. 2262): Technology and application specific, relevant characteristics.
- Ecological system: *'systems of natural flows and interactions that maintain and enhance living systems'* (p. 2262): Environmental conditions and regulations
- Institutions: "*ways of structuring human interactions' including 'regulatory frameworks, property rights and standard modes of business organisation*" (p. 2262): Forms of human interactions, regulatory frameworks, property rights and business organisation modes.
- Business strategies: "*The means and processes by which firms organise their activities so as to fulfil their socioeconomic purposes"* (p. 2262): Way of revenue generation.
- User practices: "*Routinized, culturally embedded patterns of behaviour relating to fulfilling human needs and wants*" (p. 2263). User behaviour, storage need, and utilization can influence each other based on an active or passive decision.

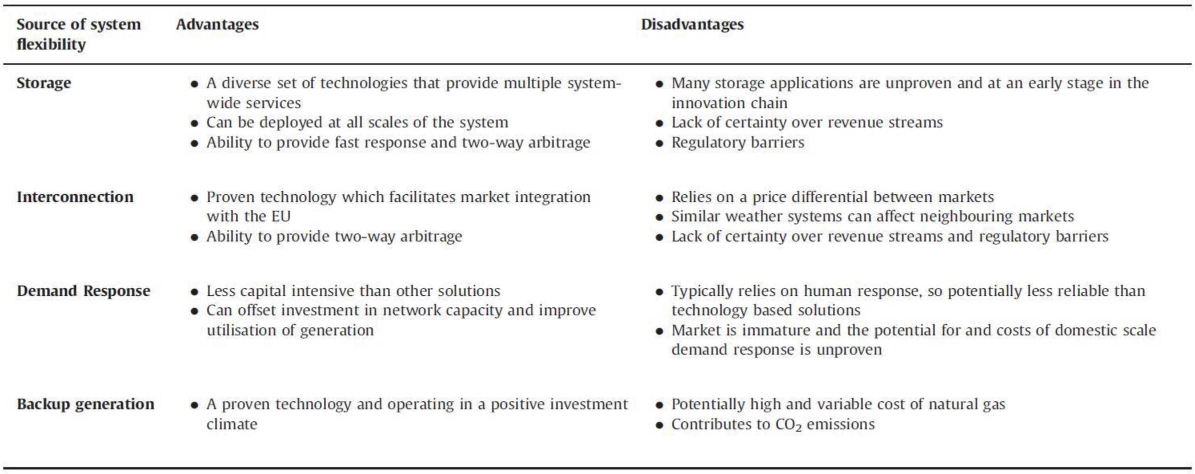
The three pathways for ESS integration are structured and characterised in the following manner, whereby a parallel realization of these scenarios is expected.

- User-led pathway
    - Driven by: Fuel prices, lack of trust in industry.
    - Actions: Installation of smart meters, residential batteries and new tariff structures which incentivise demand-side management from individuals (combination with microgeneration).
- Decentralized pathway
    - Driven by: Growing importance of medium-scale and city based energy provision, localism agenda for decentralization, low emission system incentives.
    - Actions: ESS on low and medium voltage distribution network, smart grid installation, regulatory changes, community and city-based energy provision, coevolution of institutional structures and business strategies, distribution network operators become more active.

- Centralized pathway
  - Driven by: Government provides policy framework, competitive market for private companies.
  - Actions: Large scale renewable electricity generation, electricity market reform, pumped hydro storage.

Taylor et al. (2013) also presents an analysis of competitive methods for electricity system flexibility and their pros and cons is shown in TABLE 24.

TABLE 24: ADVANTAGES AND DISADVANTAGES OF DIFFERENT SOURCES OF SYSTEM FLEXIBILITY



Source of system flexibility	Advantages	Disadvantages
Storage	• A diverse set of technologies that provide multiple system-wide services • Can be deployed at all scales of the system • Ability to provide fast response and two-way arbitrage	• Many storage applications are unproven and at an early stage in the innovation chain • Lack of certainty over revenue streams • Regulatory barriers
Interconnection	• Proven technology which facilitates market integration with the EU • Ability to provide two-way arbitrage	• Relies on a price differential between markets • Similar weather systems can affect neighbouring markets • Lack of certainty over revenue streams and regulatory barriers
Demand Response	• Less capital intensive than other solutions • Can offset investment in network capacity and improve utilisation of generation	• Typically relies on human response, so potentially less reliable than technology based solutions • Market is immature and the potential for and costs of domestic scale demand response is unproven
Backup generation	• A proven technology and operating in a positive investment climate	• Potentially high and variable cost of natural gas • Contributes to CO_2 emissions

SOURCE: Taylor et al. (2013), adapted from Taylor et al. (2012)

Beside technical performance and cost Taylor et al. (2013) names institutional environment, governance structures and user willingness to work with new technologies as key factors for innovation emergence. As conclusion Taylor et al. (2013) names the importance of combined heat and power, the high risks of long term pathways and only considering current market conditions, potential importance of public attitudes

Pricing Scheme

Zhu, Chen and Du (2014) developed a new pricing scheme by grid owners/operators which indirectly controls the operation of connected energy storage devices. The storage devices are part of a smart power system and (dis-)charged in terms of self-interested economics, whereby prices for inter day time slots are given day ahead by the grid operator. Simulations are made for a grid supplied by wind turbines, where renewable energy generation can be sold direct to the grid or stored in the ESS. The pricing scheme is proposing a way to integrate ESSs only based on prices for services, where technology specific cost structures decide on operation characteristics.

4 MATERIALS AND METHODS

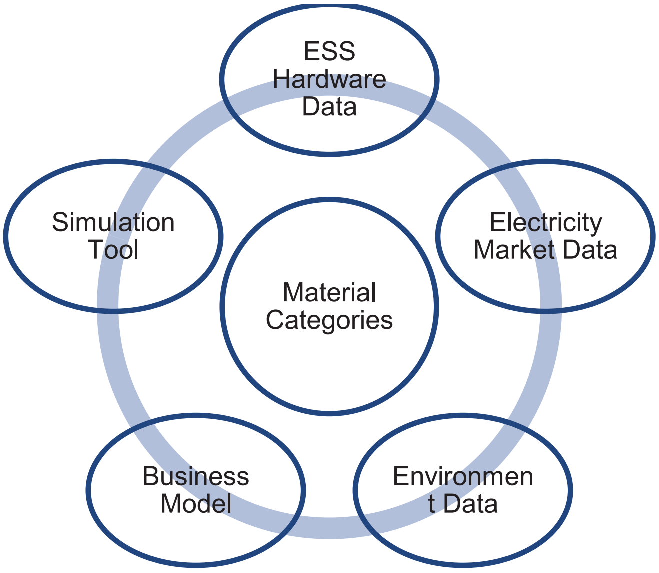
In this chapter all materials and methods, used to perform this work, are presented. The first subsection “materials” include on the one hand site, datasheets and data sets from manufacturers, institutions, resellers, open source databases and previous research and development projects. On the other hand, site, software is used to simulate and calculate the overall performance of the selected hardware.

In the second subsection the applied method to simulate the techno-economic performance of different battery system constellations under current, Brazilian market conditions and selected applications is explained.

4.1 MATERIALS

The materials, used in this study, are technical and economic data of analyses battery systems, regulations for the Brazilian electricity market, Information about considered battery system application, customers and operators, geographical and Climatological data for selected locations of potential system installations and utilized simulation software. A division in material categories, used for detailed explanations of required materials, is shown in FIGURE 40.

FIGURE 40: MATERIAL CATEGORIES

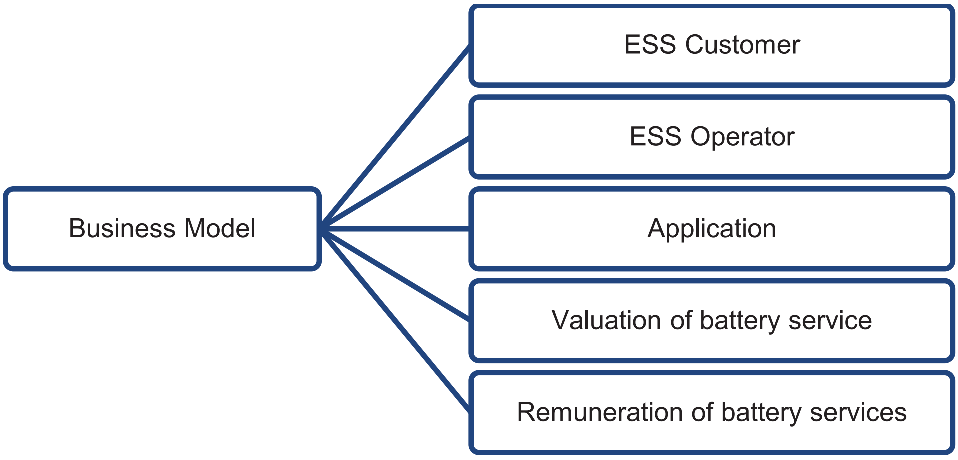


SOURCE: The author

4.1.1 Business model

The Business Model consists of a series of actors and parameters, which are grouped in ESS customer, operator, application, valuation of services and remuneration of services, as shown in FIGURE 41.

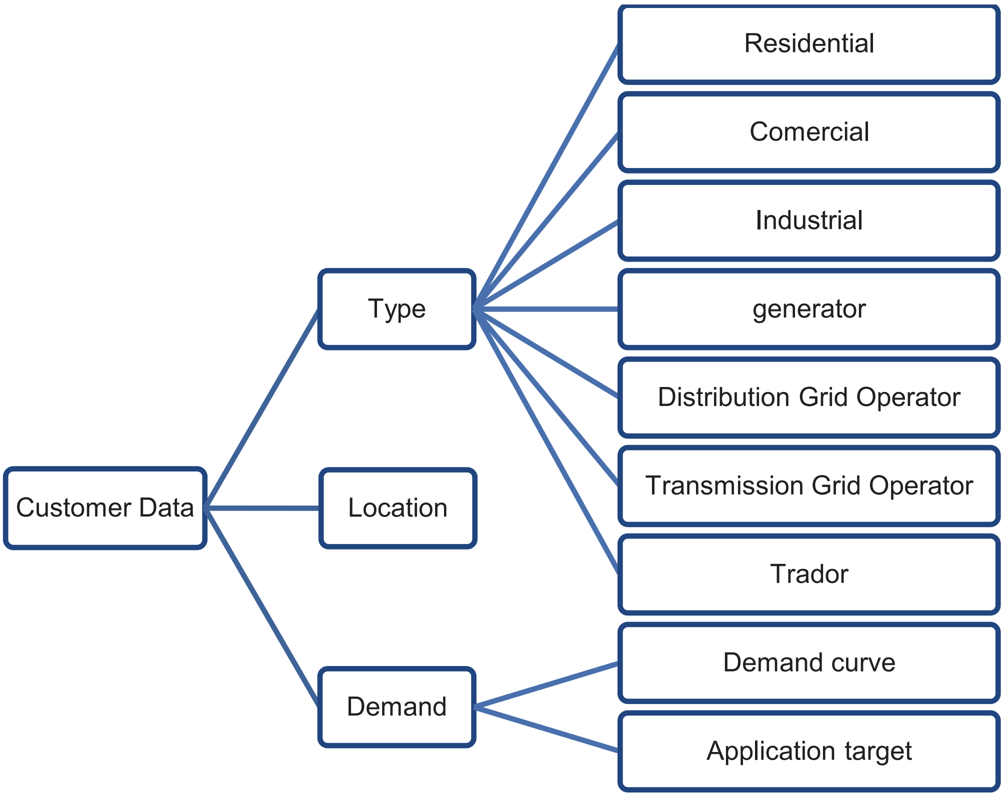
FIGURE 41: BUSINESS MODEL MATERIAL SUB-CATEGORIES



SOURCE: The author

The customer category includes all relevant information about the user of the battery ESS. This is important for technology selection and dimensioning as well as profitability calculations. Required information is given by FIGURE 42.

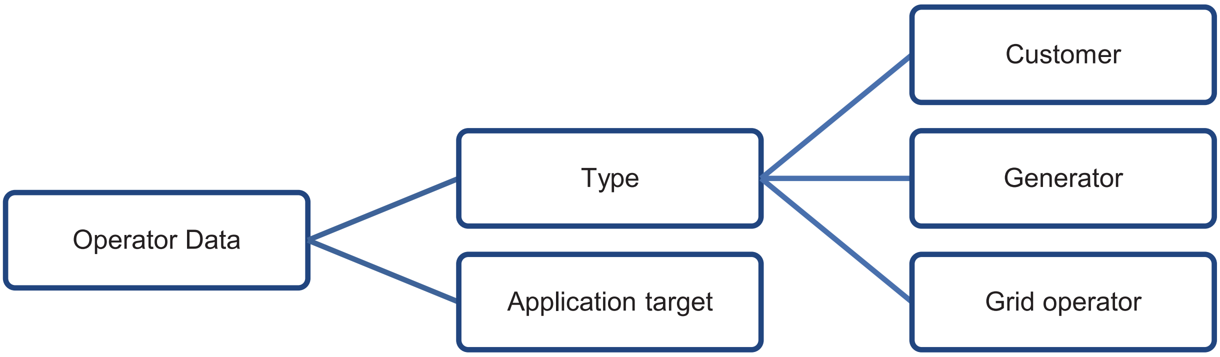
FIGURE 42: MATERIAL OF CUSTOMER CATEGORY



SOURCE: The author

The system operator is controlling the ESS devise and therefore firstly taking important decisions in relation to profitability and lifetime of the battery and secondly playing an important role of the selected business model. The materials required for simulations are presented in FIGURE 43.

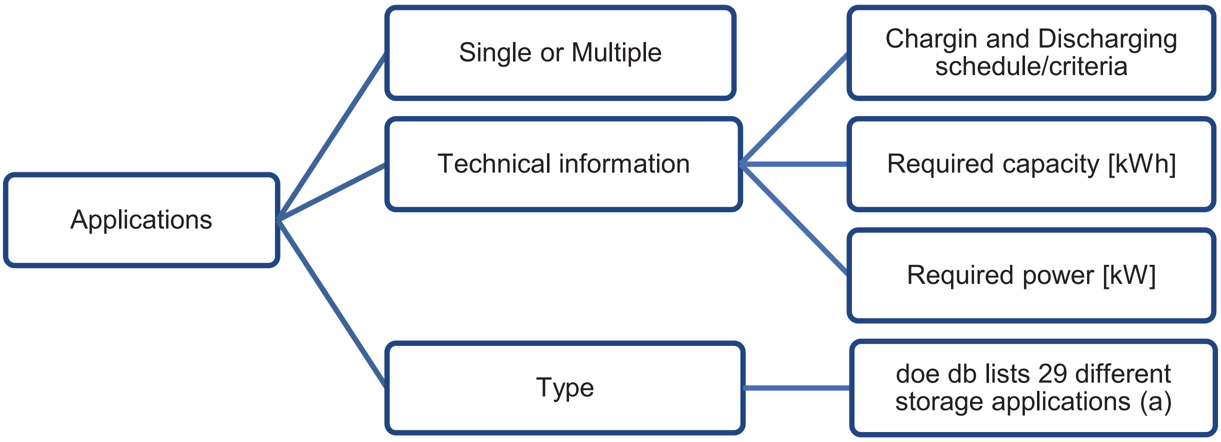
FIGURE 43: MATERIAL OF SYSTEM OPERATOR CATEGORY



SOURCE: The author

The form of application for the ESS is presenting the way, in which the battery service satisfies a wish or solves a problem of the user or stakeholder of the system. Battery application selection presents one of the hugest influences on the choice of technology, its performance and lifetime, as well as the profitability. Systems can be operated in a single or multiple application. Relevant application criteria are presented in FIGURE 44.

FIGURE 44: MATERIALS OF APPLICATIONS CATEGORY



SOURCE: The author

An overview of different application types for energy storage technologies, based on the energy storage database from department of energy from the USA, is given in TABLE 25.

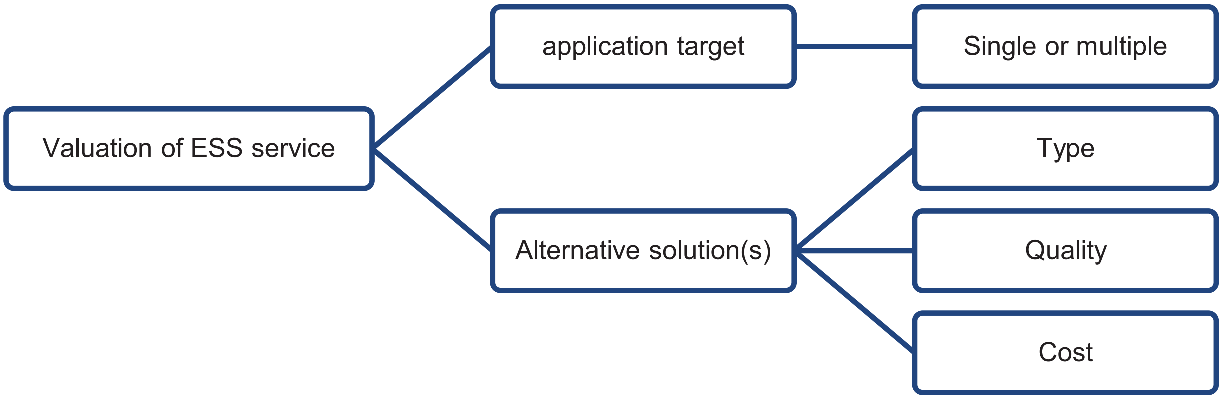
TABLE 25: STORAGE APPLICATION TYPES

Storage Applications
Black Start
Electric Supply Reserve Capacity - Non-Spinning
Electric Supply Reserve Capacity - Spinning
Load Following (Tertiary Balancing)
Ramping
Voltage Support
Electric Energy Time Shift
Electric Supply Capacity
Transmission Congestion Relief
Transmission Support
Renewables Capacity Firming
Distribution upgrade due to solar
Distribution upgrade due to wind
Transmission upgrades due to solar
Transmission upgrades due to wind
Electric Bill Management
Grid-Connected Commercial (Reliability & Quality)
Grid-Connected Residential (Reliability)
Frequency Regulation
Transportable Transmission/Distribution Upgrade Deferral
Stationary Transmission/Distribution Upgrade Deferral
Onsite Renewable Generation Shifting
Electric Bill Management with Renewables
Renewables Energy Time Shift
On-Site Power
Transportation Services
Microgrid Capability
Resiliency
Demand Response

SOURCE: Sandia national laboratories (2016)

The valuation of battery services is crucial for the calculation of system economics and differs from case to case (Figure 45).

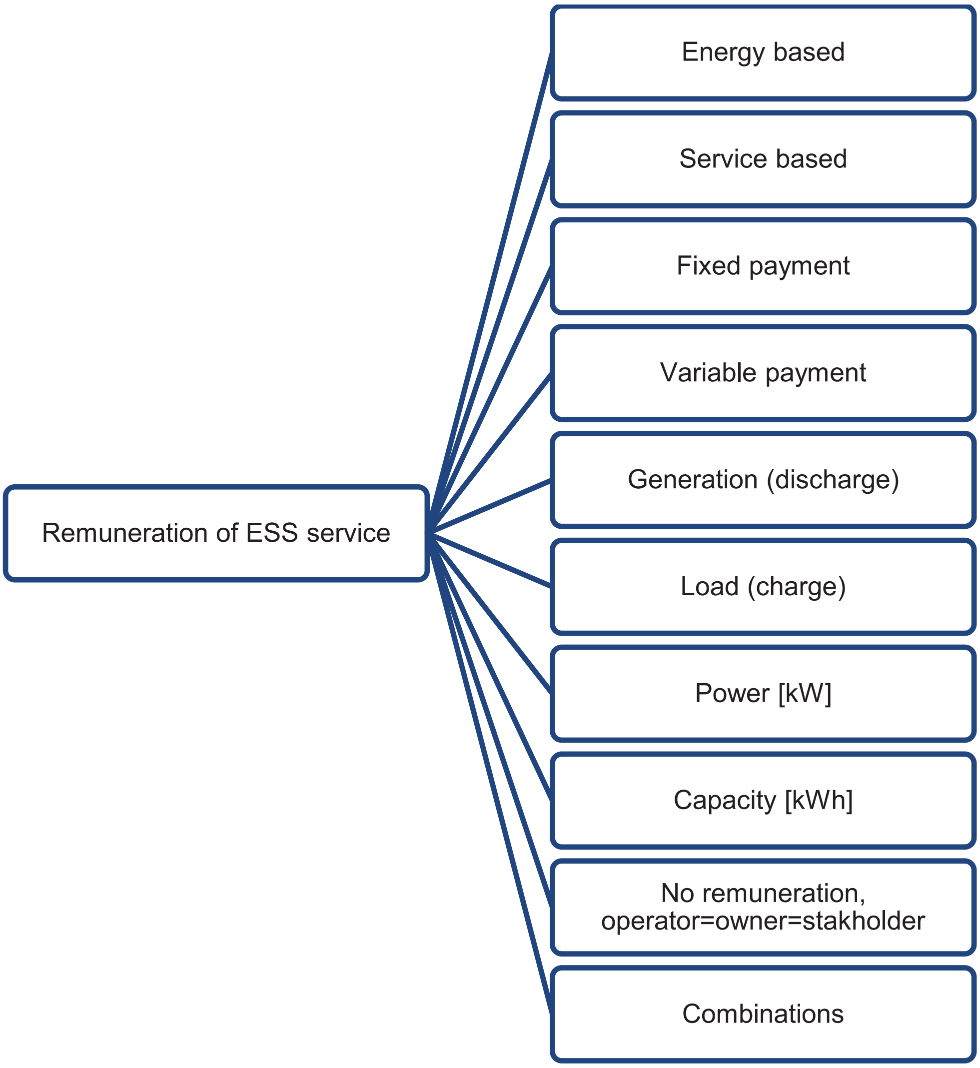
FIGURE 45: MATERIALS OF VALUE OF ESS SERVICES



SOURCE: The author

Like traditional generators, which can be remunerated in terms of electricity production or potential availability, beside the valuation of ESS services also the way of remuneration is an important criterial. Different possibilities, which must be known for revenue calculations, are shown in FIGURE 46.

FIGURE 46: MATERIAL OF REMUNERATION OF ESS SERVICE

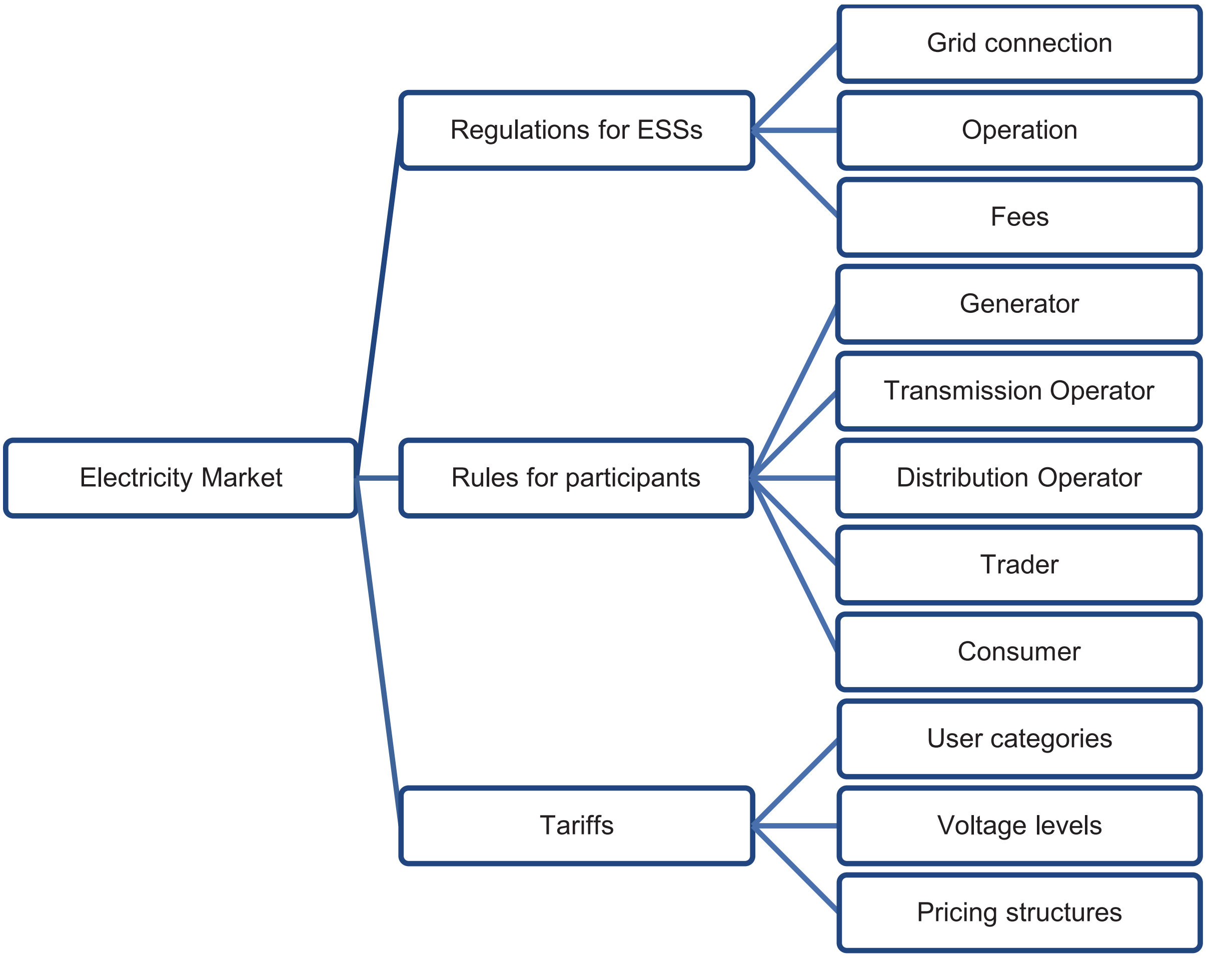


SOURCE: The author

4.1.2 Electricity Market

The second category, electricity market, contains important information about the market structures, regulatory frameworks, and electricity tariffs. Basic materials for this work are Nery (2012) and ANEEL regulations, available under ANEEL (2017a), see FIGURE 47.

FIGURE 47: MATERIALS OF ELECTRICITY MARKET

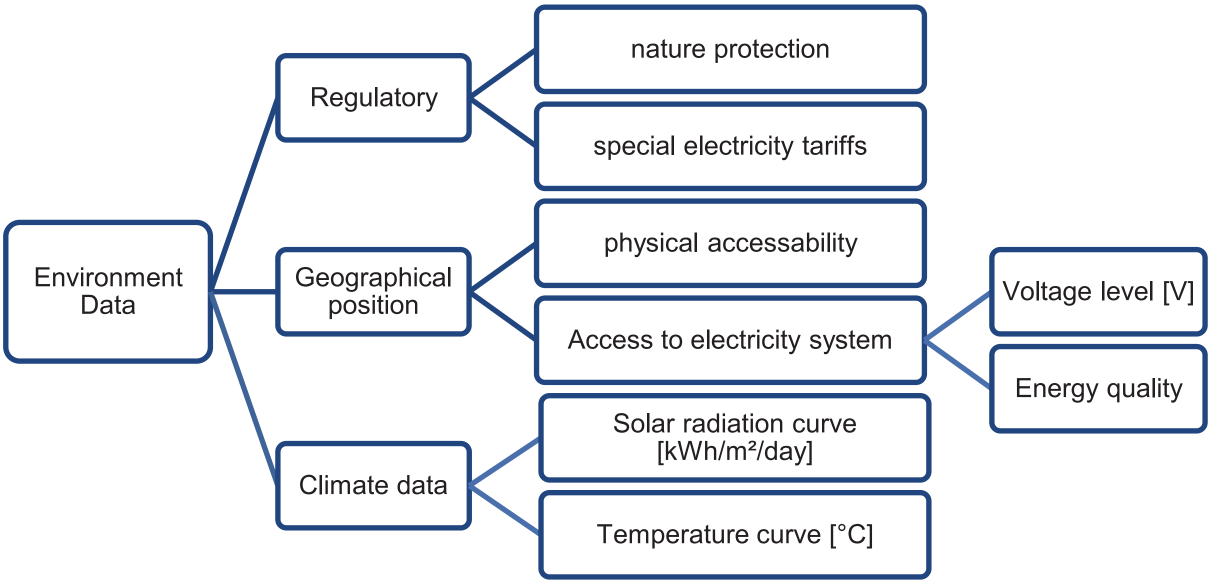


SOURCE: The author

4.1.3 Environment

The environment of the intended ESS installation is not only important due to access and regulations for nature conservation, but also for technical system performance and cost calculations. Information to be considered in terms of environment is shown in FIGURE 48.

FIGURE 48: MATERIAL OF ENVIRONMENT CATEGORY

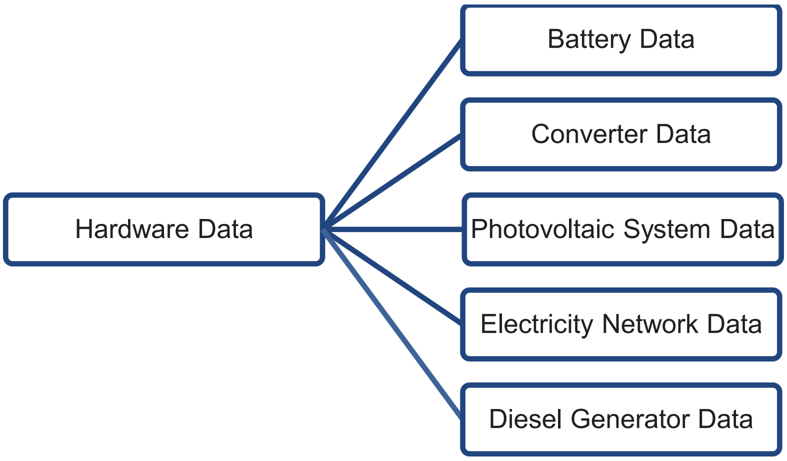


SOURCE: The author

4.1.4 Hardware

The category “ESS Hardware” includes technical and economic materials, required to analyses hardware of the battery systems, including all related components to set up desired electrification infrastructures, as well as components which could provide alternative solutions to the battery systems. A further splitting of the term ESS Hardware in sub-categories is shown in FIGURE 49.

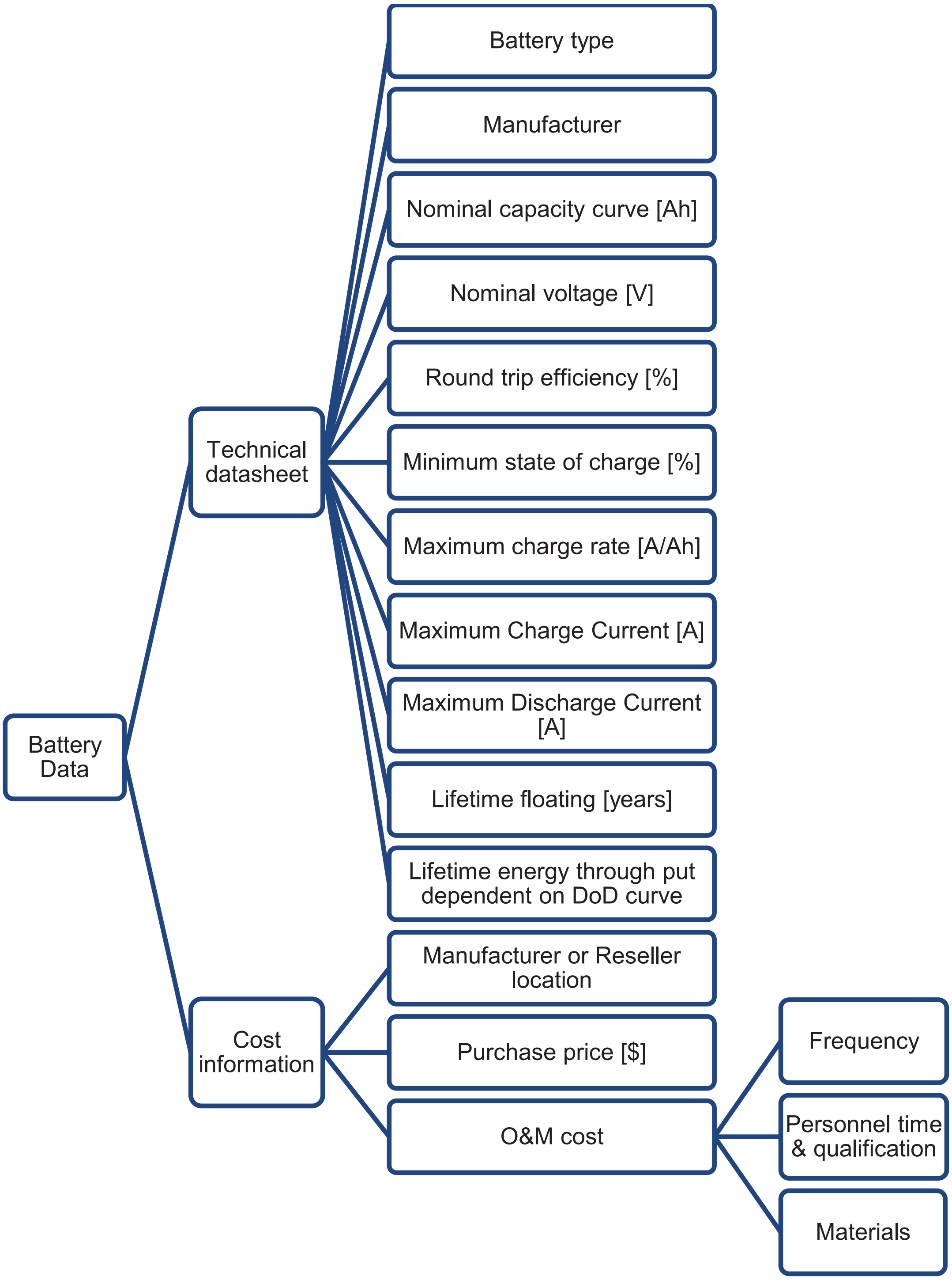
FIGURE 49: MATERIALS OF HARDWARE CATEGORY



SOURCE: The author

The different Hardware components, which are considered for performance simulations in the next chapter of this work, are further detailed in terms of required technological and economical information, as presented in figures 50 to 54.

FIGURE 50: MATERIALS FOR BATTERY COMPONENT

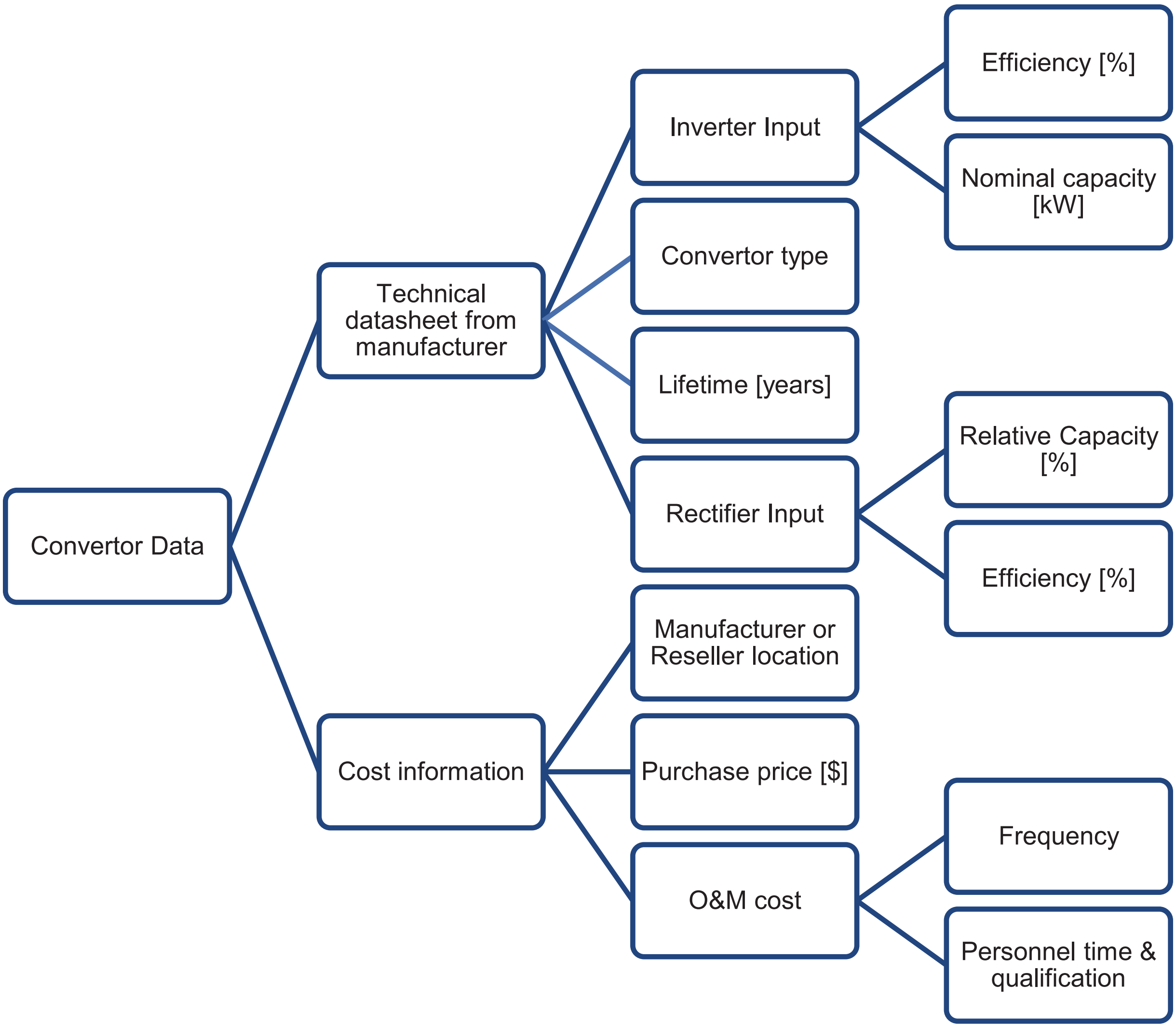


SOURCE: The author

Since battery performance shows high sensitivity in relation to various utilization characteristics, a series of technical specifications are necessary, compare FIGURE 50. This information can usually be found in the product datasheet, which is usually provided by the manufacturer. Economic data are directly related to the purchasing location, sales concept, product volume and market regulatory in terms of incentivisation programs or customs duties.

Convertors are required for AC-DC interfaces and therefore required for batteries as well as PV modules. In this work the convertors are assumed to include a maximum power point tracking (MPPT) system in case of PV and optimum power point tracking (OPPT), in case of PV for battery charge utilization. Used data for simulations are summarized in FIGURE 51.

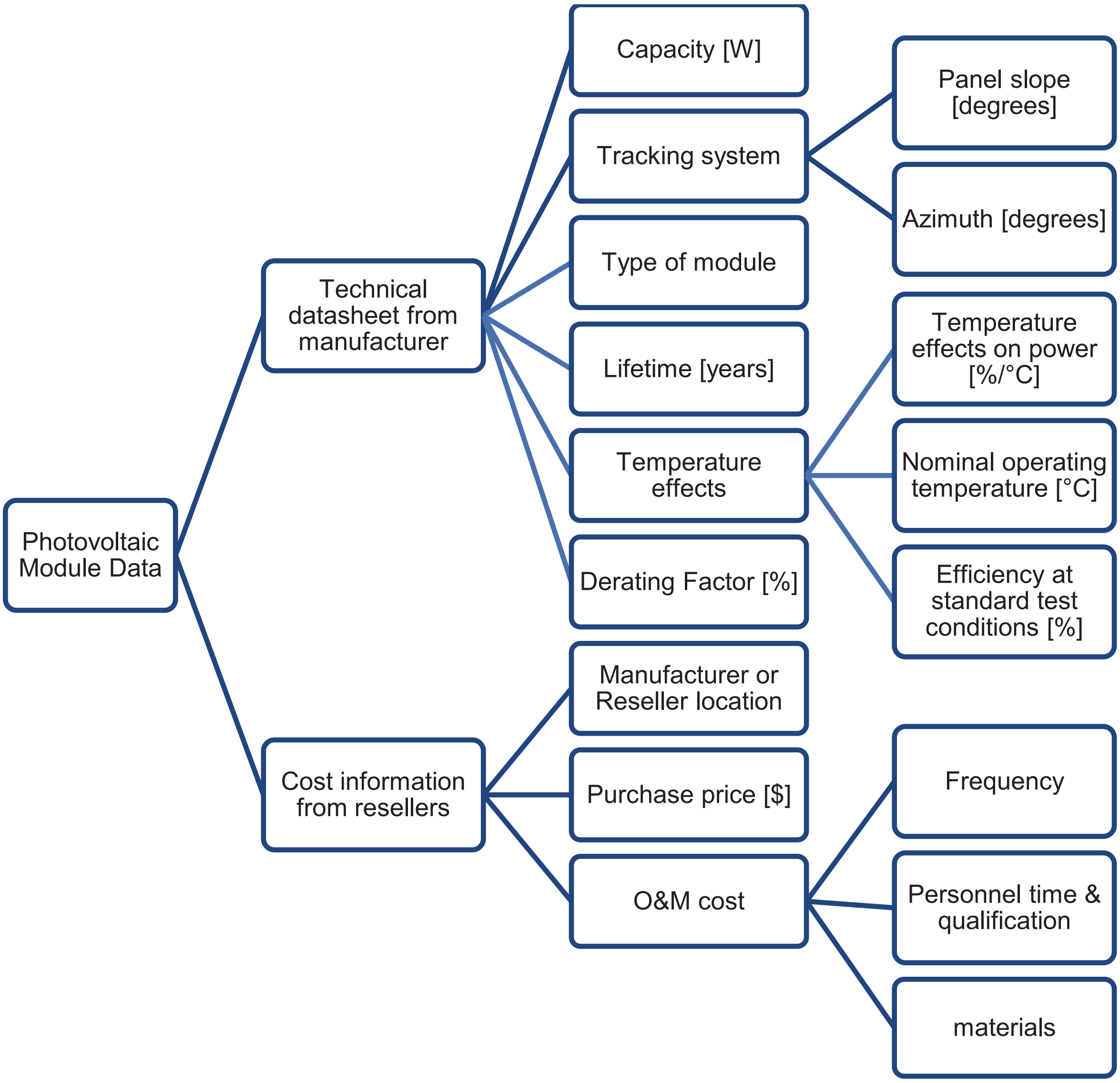
FIGURE 51: MATERIALS FOR CONVERTOR COMPONENT



SOURCE: The author

The photovoltaic module is an optional component, which can be used as part of the battery based electrification system. Technical performance is dependent on criteria like module and installation type and external influences, such as climate and location and orientation. Investment prices depend on technology and origin, whereby operation and maintenance cost are strongly dependent on location. Technical information is provided by manufacturer datasheet, whereby economic values need to be taken from current reseller prices. Relevant material is summed up in FIGURE 52.

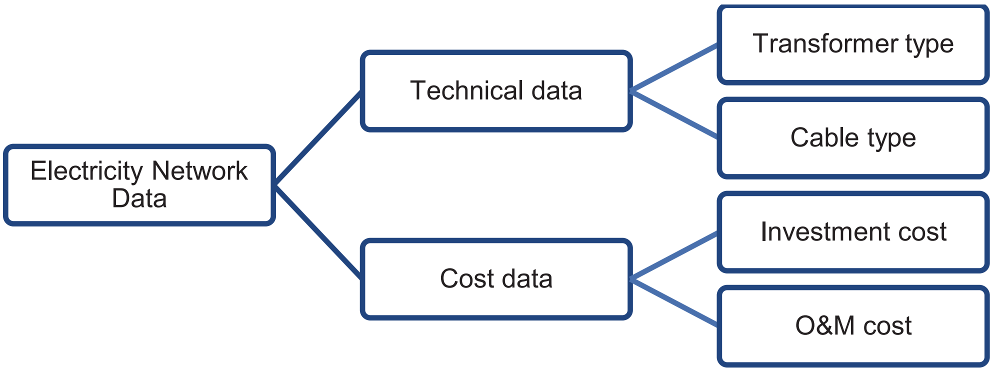
FIGURE 52: MATERIALS FOR PHOTOVOLTAIC COMPONENT



SOURCE: The author

Material about electricity networks is used for cost comparison between battery system utilization and conventional methods of grid reinforcement or extension. Therefore, only basic values are considered, to calculate case specific costs in form of price per distance at certain electricity capacity and quality requirements. Data needed therefore are shown in FIGURE 53.

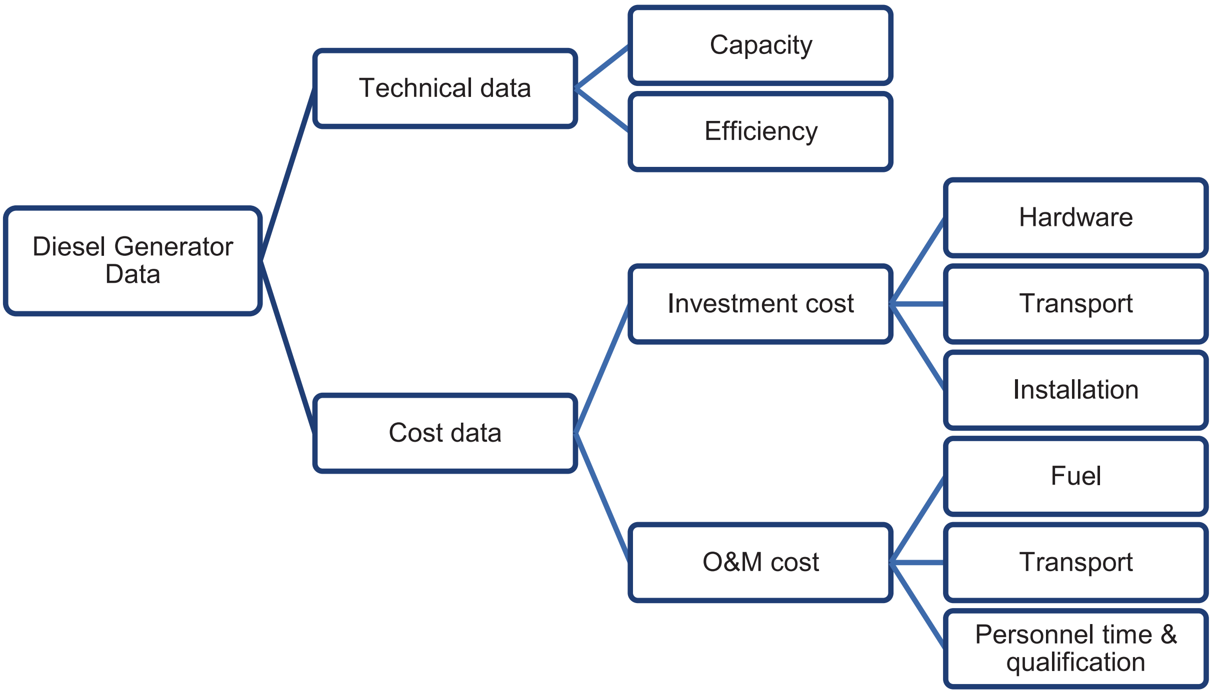
FIGURE 53: MATERIAL FOR ELECTRICITY NETWORK COMPONENT



SOURCE: The author

Diesel generators are conventional solutions to deliver electricity services in applications, favourable for battery system operation. Therefore, the system costs, using diesel generators are used for comparative analysis to ESS solutions. Technical performances, such as overall efficiency or lifetime, of combustion engines are heavily dependent on operation mode. System cost are, beside efficiency factor and fuel costs, strongly dependent on-site location, due to great varieties of transport and travel costs. The required materials for comparative calculations are shown in FIGURE 54.

FIGURE 54: MATERIAL FOR DIESEL GENERATOR COMPONENT



SOURCE: The author

4.1.5 Simulation program

Finally, to process all this material, a simulation program is needed. In this work the microgrid simulation and optimization software Homer Energy, version is Homer Pro 3.6.1 and available under Homer Energy (2017), is used to calculate the overall battery system costs.

FIGURE 55: HOMER ENERGY LOGO

SOURCE: Homer Energy (2017)

The program combines technical, economic and climate data to enable the simulation of energy system operation under flexible framework conditions. All parameters required by the software are already listed in the previous part of the sub-chapter of materials.

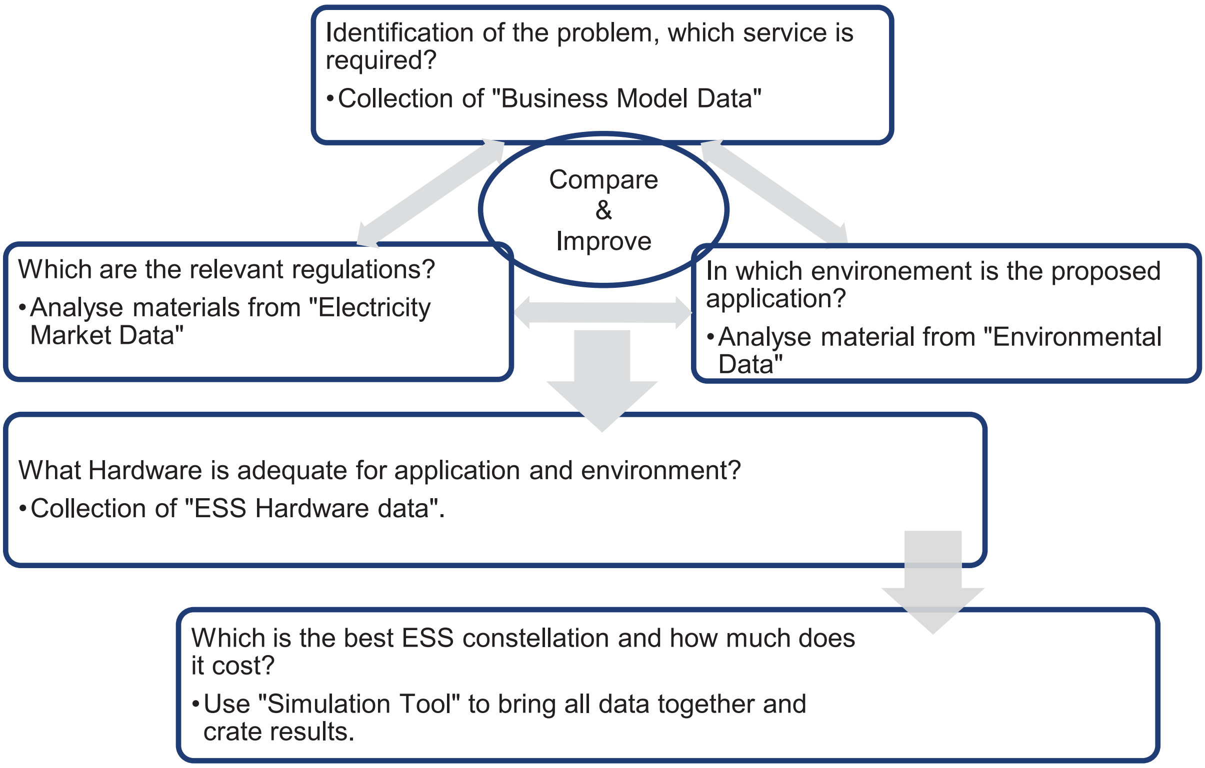
4.2 METHODS

In this chapter the method, how the selected materials are used to generate new information is described. This includes the whole process, applied to simulate the data selection for the desired battery energy storage system, the mounting of the system, inclusive dimension of the single components, the overall cost calculation and comparison with conventional electrification methods.

The simulation software Homer Energy is used to set up different battery storage systems to check the technical feasibility in terms of electric power and energy, to fulfil the desired service of selected customer applications. Furthermore, the system costs are calculated with the annuity method as an internal function of Homer Energy, taking into consideration site specific environmental framework conditions. The program is also used to perform system optimizations to identify favouring components and constellations in respect to overall utilization targets. Following the method, explained in this chapter, allows the reproduction of all results, presented in chapter 0.

An overview of the applied method is given by FIGURE 56.

FIGURE 56: METHOD FOR DISTRIBUTED ESS SIMULATIONS



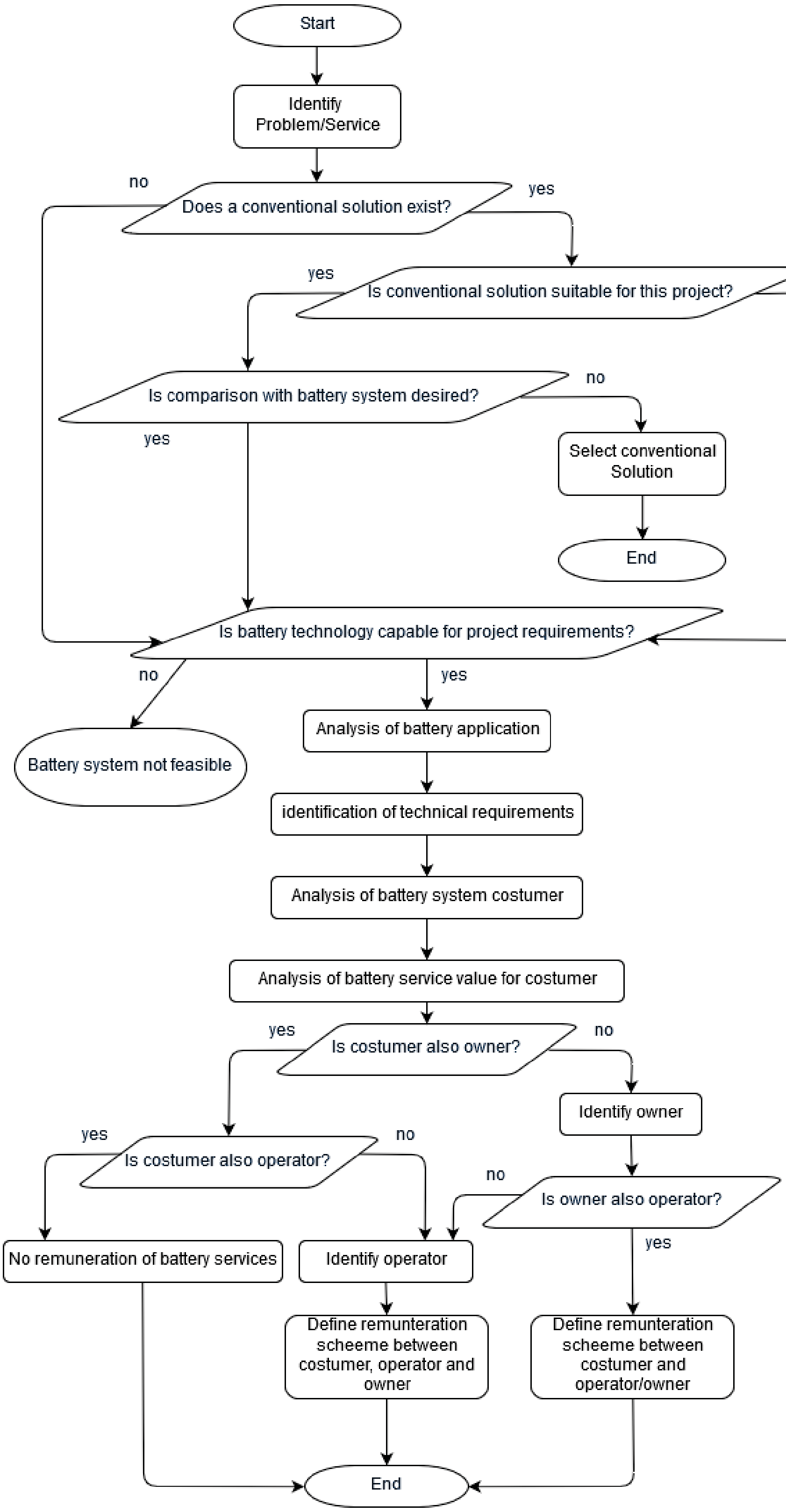
SOURCE: The author

4.2.1 Business Model

As a first step the problem to be solved or service to be required needs to be identified, to analyse if an ESS can be a solution from a technical point of view. In general, the solution, the storage devise delivers are named the application. At this point most probably, the customer is already known. In case, the customer is not expected to be responsible for investment and operation, then the operator and or service trader needs to be identified. Knowing the application, owner, operator and customer, the value of the service needs to be evaluated. The evaluation of the service value can be defined by opportunity costs, compared to the cheapest alternative solution, or based on reduction of current or expected future costs, due to battery system integration. Is the position of operator, consumer and owner not occupied by the same person or institution, than the way of service remuneration needs to be defined as a final step.

The decision criteria for distributed battery storage utilization are limited to various criteria. The following flowchart, FIGURE 57, is used in this work as method, to combine relevant business model material.

FIGURE 57: METHOD FOR BATTERY SYSTEM BUSINESS MODEL DATA COLLECTION



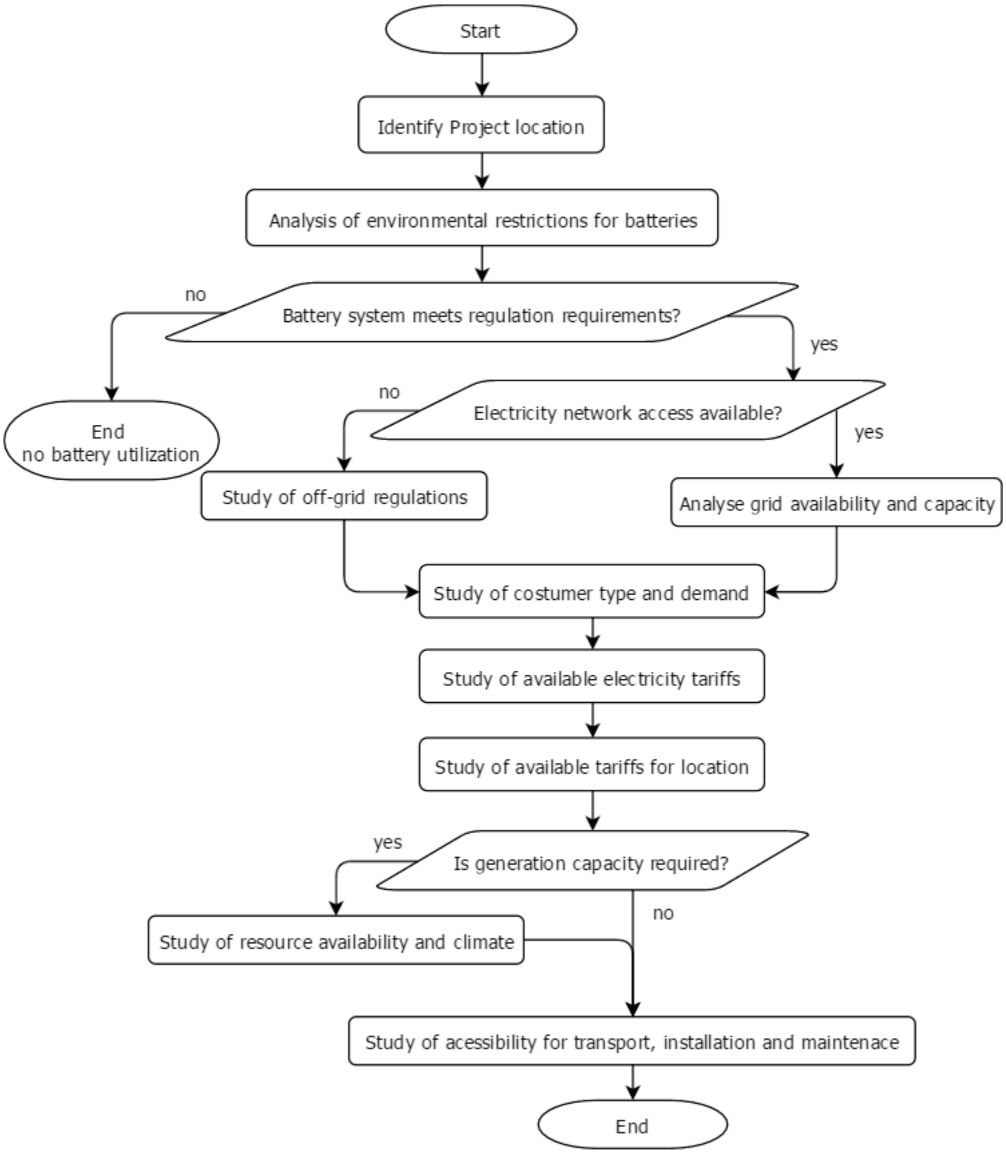
SOURCE: The author

4.2.2 Project Environment

The environment of the intended distributed battery storage project needs to be known to take the right decisions on suitable technologies, system dimensions, cost structures and viability, analysis of alternatives for identified application and regulations as well as restrictions in terms of nature protection and electric energy system. First of all, the project location has to be known, to analyse the availability of alternative solutions, such as access to distribution network, energy resources, inclusive renewables, climate data and transportation ways to the destination. The environmental regulations need to be studied, to identify regulations that influence the installation of battery systems or alternative solutions. These factors might have positive or negative impacts on suitability of battery systems. Based on this information, a first tendency for or against storage and generation system types can be identified.

The method, used in this work, to collect relevant data for battery system utilizations in terms of the project environment is presented in FIGURE 58.

FIGURE 58: METHOD FOR BATTERY SYSTEM ENVIRONMENT DATA COLLECTION



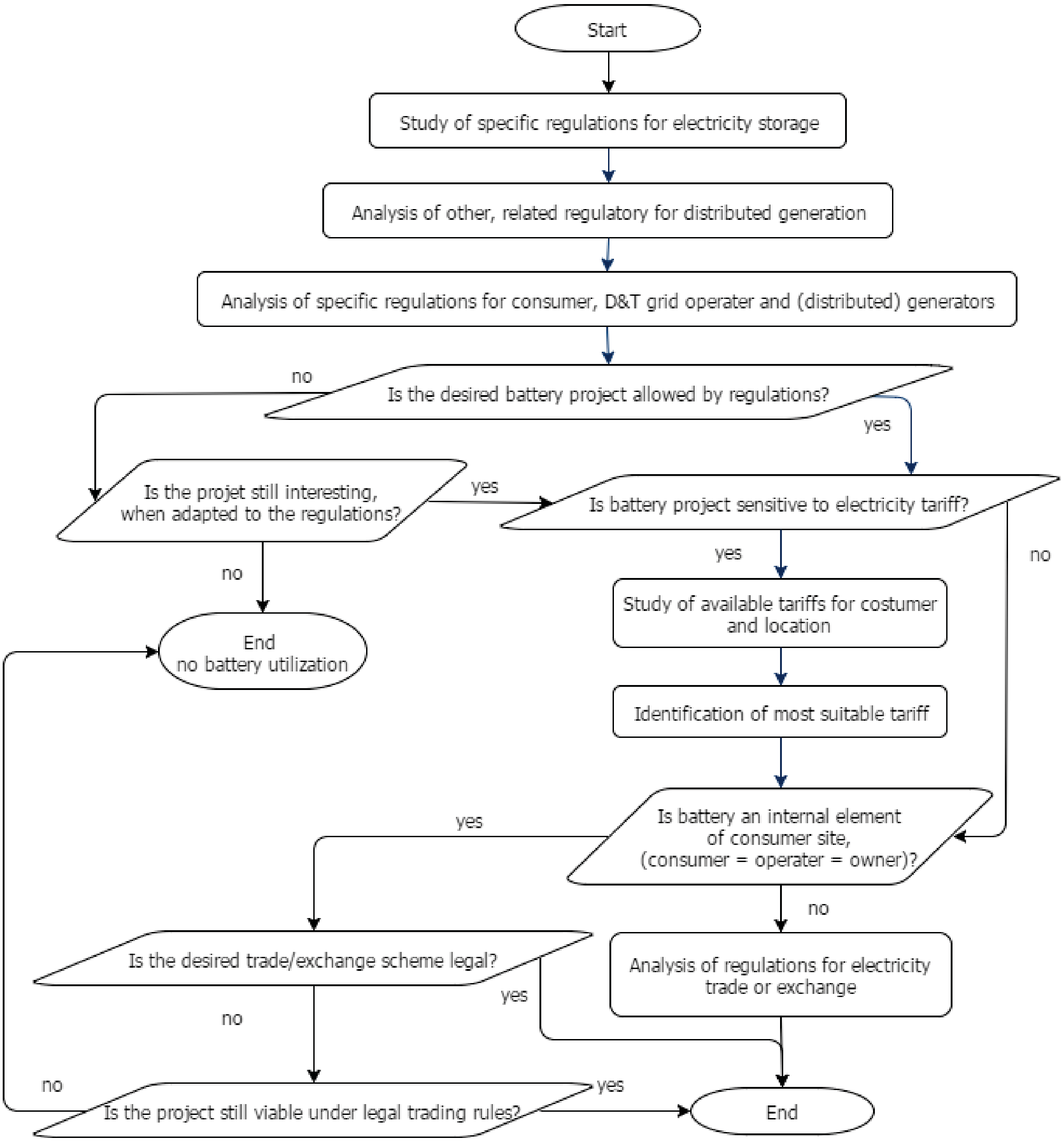
SOURCE: The author

4.2.3 Electricity Market Regulations

The electricity markets are regulated in terms of generation, transmission, distribution, trading and consumption. For each distributed battery storage application, the interaction with regulations must be studied. This is valid firstly in terms of technical operation and grid connection of storage devises, to interact with other participants of the electricity network, and exchange electric energy. But also, secondly in terms of electricity trade, sell, buy or any remuneration concept. At this point especially, the ownership and operation of the storage advice must be considered, due to restrictions and special regulations for T&D network operators and for different consumer classifications. Depending on consumer classes the influence of tariff structures must be considered, this includes not only different prices for electricity consumer but also special regulations for distributers, which have influence on system performance requirements, sizing or costing structures.

The method, to collect the relevant data in relation to the electricity market regulations for distributed battery storage systems, as utilized in the work, is shown in FIGURE 59.

FIGURE 59: METHOD FOR BATTERY SYSTEM ELECTRICITY MARKET DATA COLLECTION

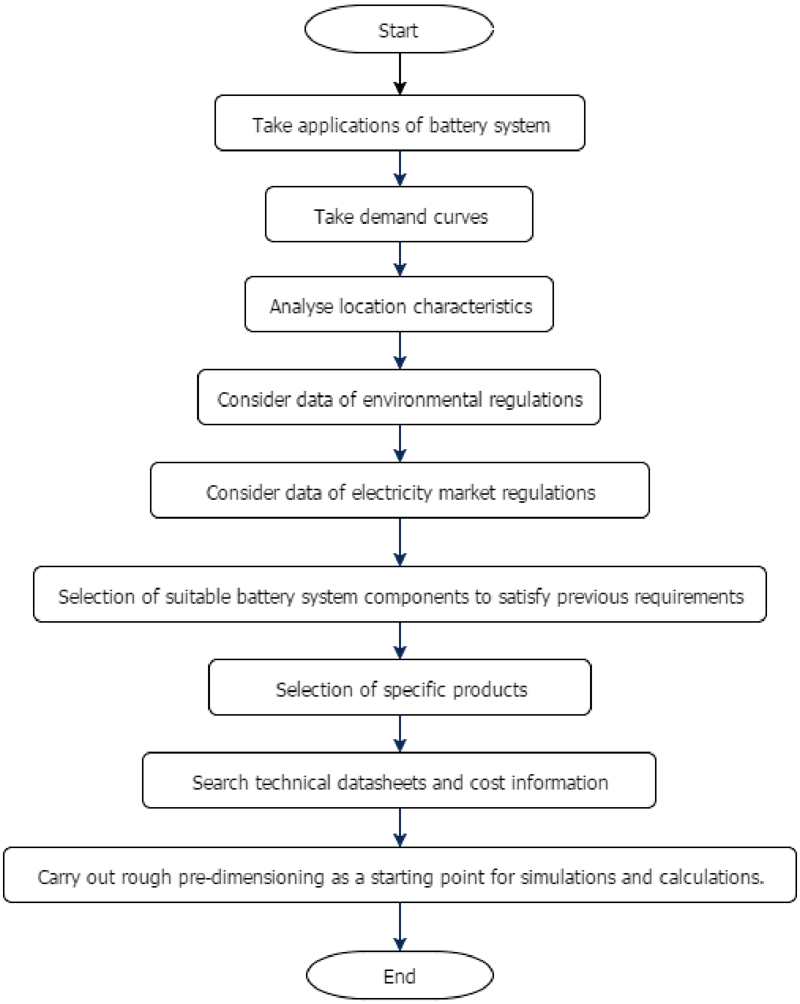


SOURCE: The author

4.2.4 ESS Hardware Selection

The selection of the right battery system depends on various criteria, where the collected information on business model, environment and electricity market play an important role. This way, a preselection of appropriate technologies can be made, based on the desired application, capacity, system location, including temperature and accessibility for transportation and maintenance works, market and price situation. This is also valid for additional system components, which might be used in combination with the storage device, such as renewable or diesel generator units or converters. Based on a preselection, which can also be motivated by personal interests, political interests or business cooperation, it can still be advantageous, to consider different technologies, manufacturers and system constellations for the cost and performance simulations. FIGURE 60 presents the method of battery system hardware selection for all simulations, elaborated in this thesis.

FIGURE 60: METHOD FOR BATTERY SYSTEM HARDWARE DATA COLLECTION

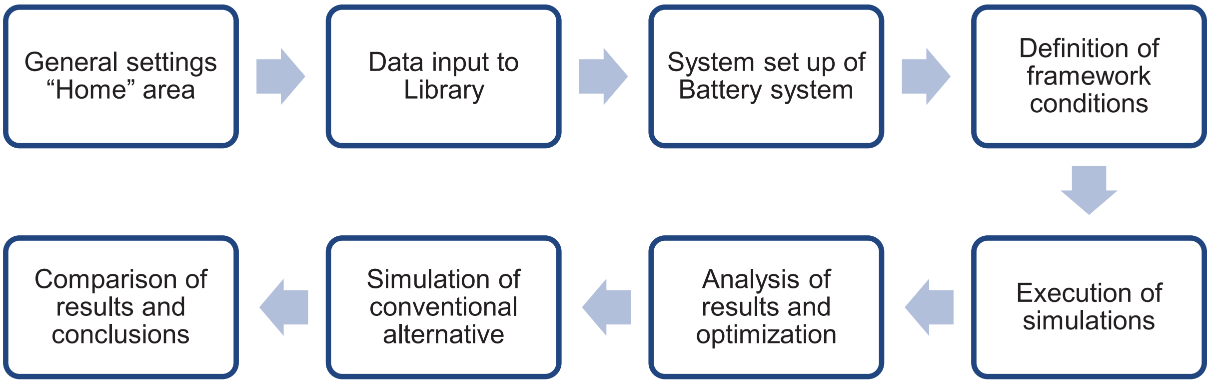


SOURCE: The author

4.2.5 Simulation Tool

The overall procedure to simulate and create results is realized, executing the detailed proceedings of all sub points, belonging to the macro steps, shown in FIGURE 61.

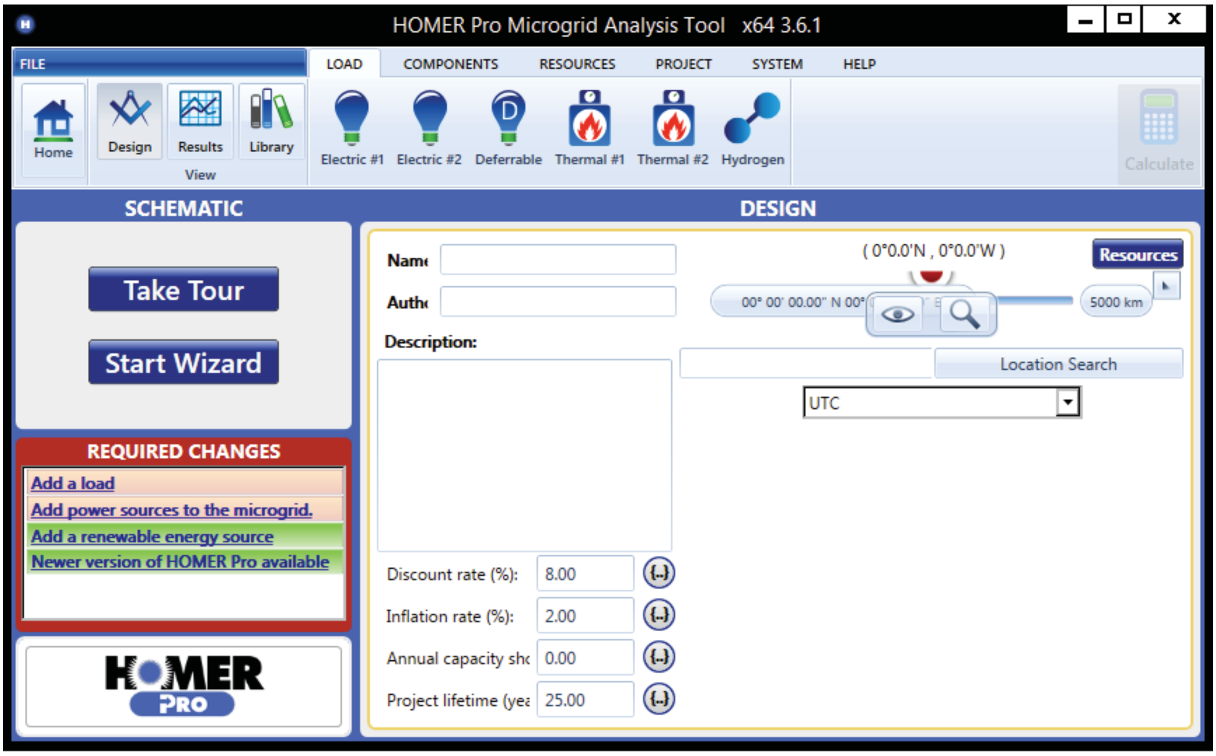
FIGURE 61: OVERALL SIMULATION METHOD



SOURCE: The author

The simulation program is structured into the view sections Home, Design, Results and Library Selection. The working surface with an overview of available categories is presented in FIGURE 62.

FIGURE 62: HOMER ENERGY WORKING SURFACE



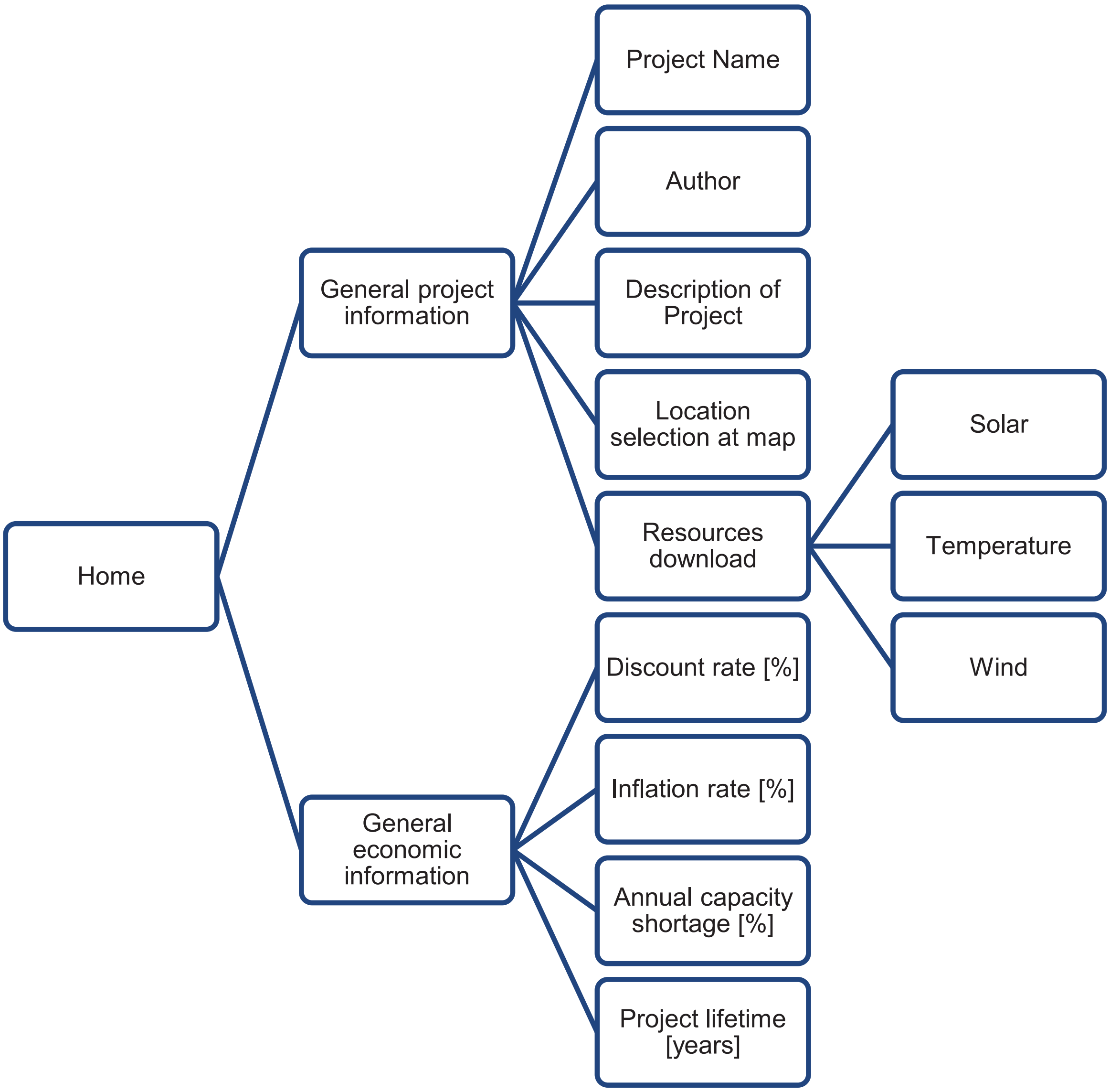
Add a load
Add power sources to the microgrid.
Add a renewable energy source
Newer version of HOMER Pro available

Discount rate (%): 8.00
Inflation rate (%): 2.00
Annual capacity sh 0.00
Project lifetime (yea 25.00

SOURCE: Homer Energy (2017)

The "Home" area is used to set general project information, specific resource upload and platform to montane the components of the electrification system. The Design area is not utilized for during the simulations undertaken in this study. The area “Results” provides detailed information about technical as well as economic performance of all suitable system constellations and allows optimizations and categorized analysis. The Library area is used to insert general data sets, which during system set up can be imported to the current project. FIGURE 62 shows the “Home” screen, where initial settings must be done, as shown in FIGURE 63.

FIGURE 63: GENERAL SYSTEM SETTINGS FOR SIMULATION

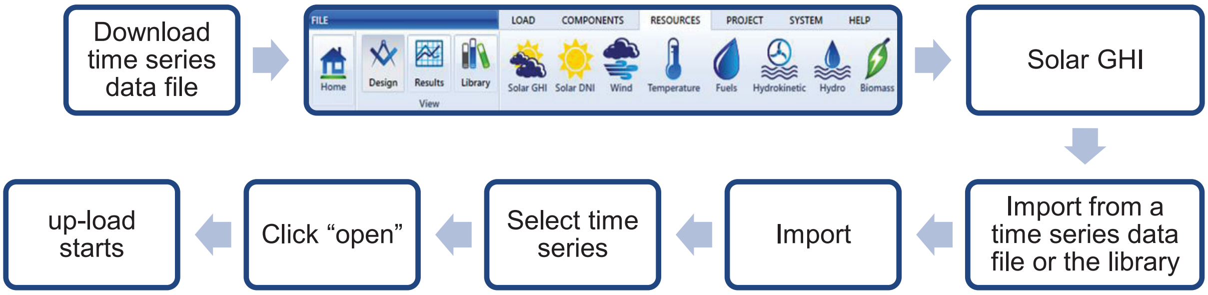


SOURCE: Homer Energy (2017)

The general economic data are selected equal for all simulation to guarantee comparability of results. The general project data are used to save all simulations as separate projects, what is necessary because of individual system configurations.

This includes the resources data, about solar radiation, fuel costs, temperature curves and wind speed at the selected system location. Climate data can be imported directly for each project, by selection of the project location and import of historic datasets from the NASA. This data gives monthly average values for solar global horizontal irradiance and temperature from the year 1983 until 2005. Data curves can be uploaded to the library, using the path shown in FIGURE 64.

FIGURE 64: RESOURCE DATA IMPORTATION TO LIBRARY PROCESS



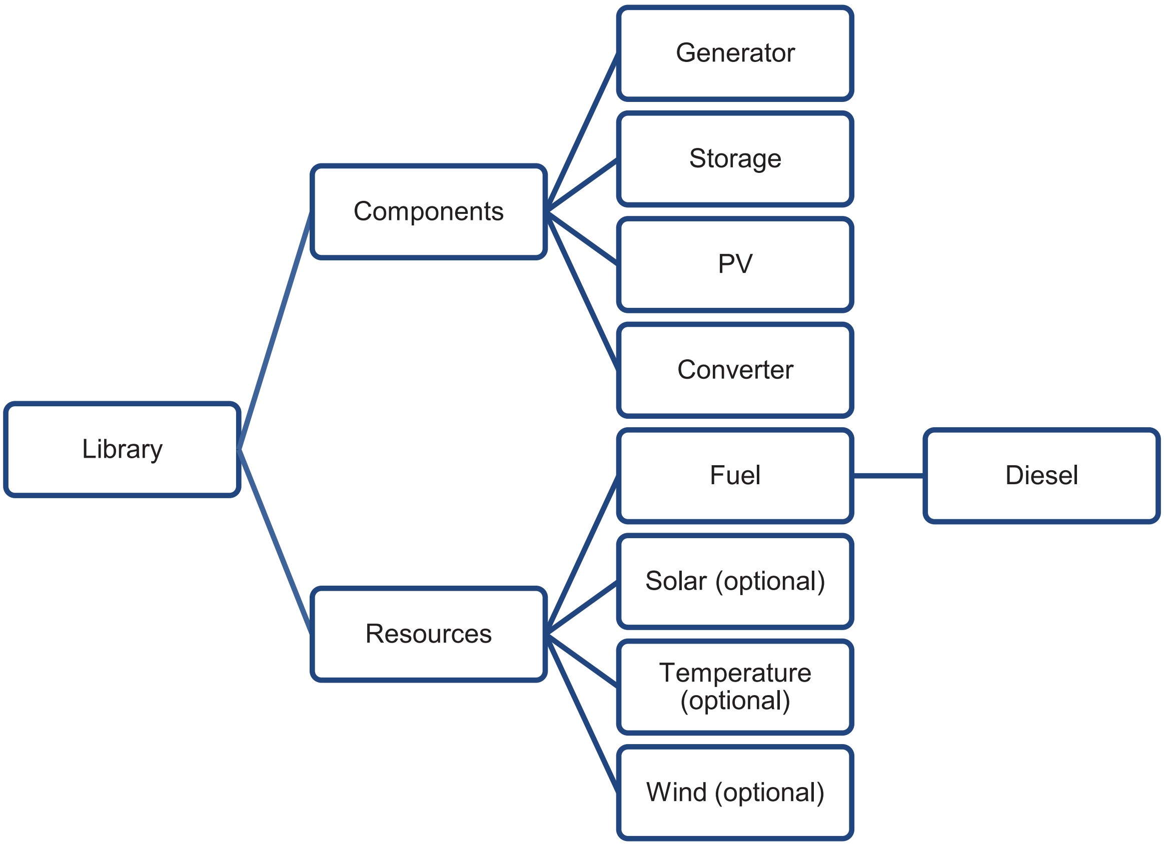
SOURCE: Homer Energy (2017)

Since the impact of temperature on system is critical in relation to efficiency and lifetime, more detailed curves lead to higher value of representation of results.

Library

After selection and insertion of all data and information shown in FIGURE 63, the library must be feed with relevant data. This data can later be accessed to mountain various simulation projects to compare variations in system parameters and combinations. This includes information about all system components, resources, load and grid, as already presented in chapter 4.1. The data input is done step by step for all sub-categories presented in FIGURE 65.

FIGURE 65: LIBRARY DATA INPUT FOR SIMULATIONS

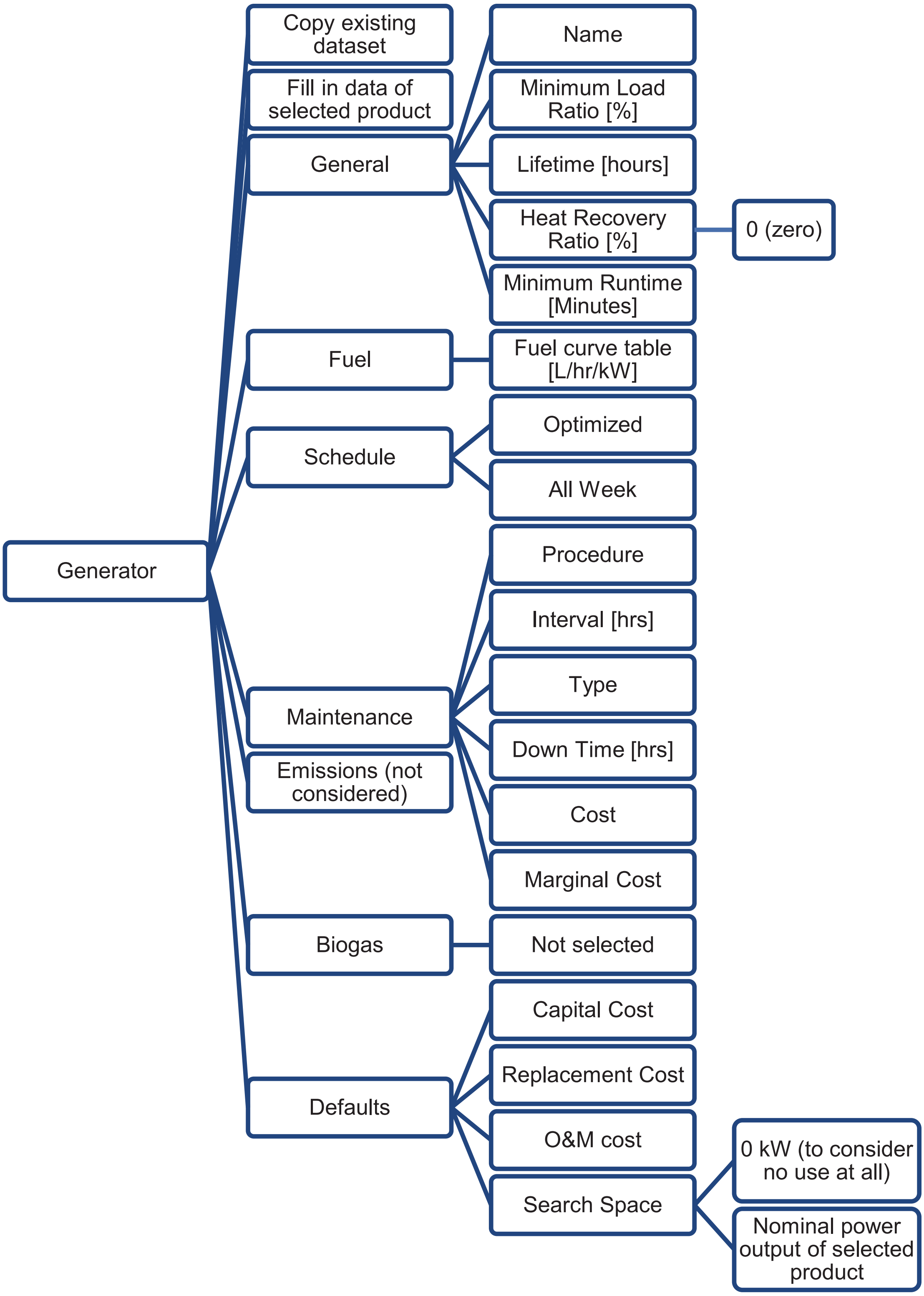


SOURCE: Homer Energy (2017)

Starting with the components, technical and economic data must be filled in the library to be available for selection in the next step of system composition. Generally, the difference between capital or investment costs compared to the replacement costs for the components is based on the initial cost of installation. This includes hardware and personnel costs for civil works, under constructions for PV systems and housings for batteries, as well as cables and installation. As a simplified approach to calculate the personnel costs for installation and minor electrical materials, a factor of 30 % of the hardware components is considered.

The generator can be used as active part of the analysed electricity system or for a separate simulation for the same application, to serve as a reference technology for economic performance comparison. Based on the system specific criteria the desired product must be selected and technical data, costs and system operation parameters chosen. An overview of relevant settings, made in this study step by step, to use the generator only to create comparative cost information, is given in FIGURE 66.

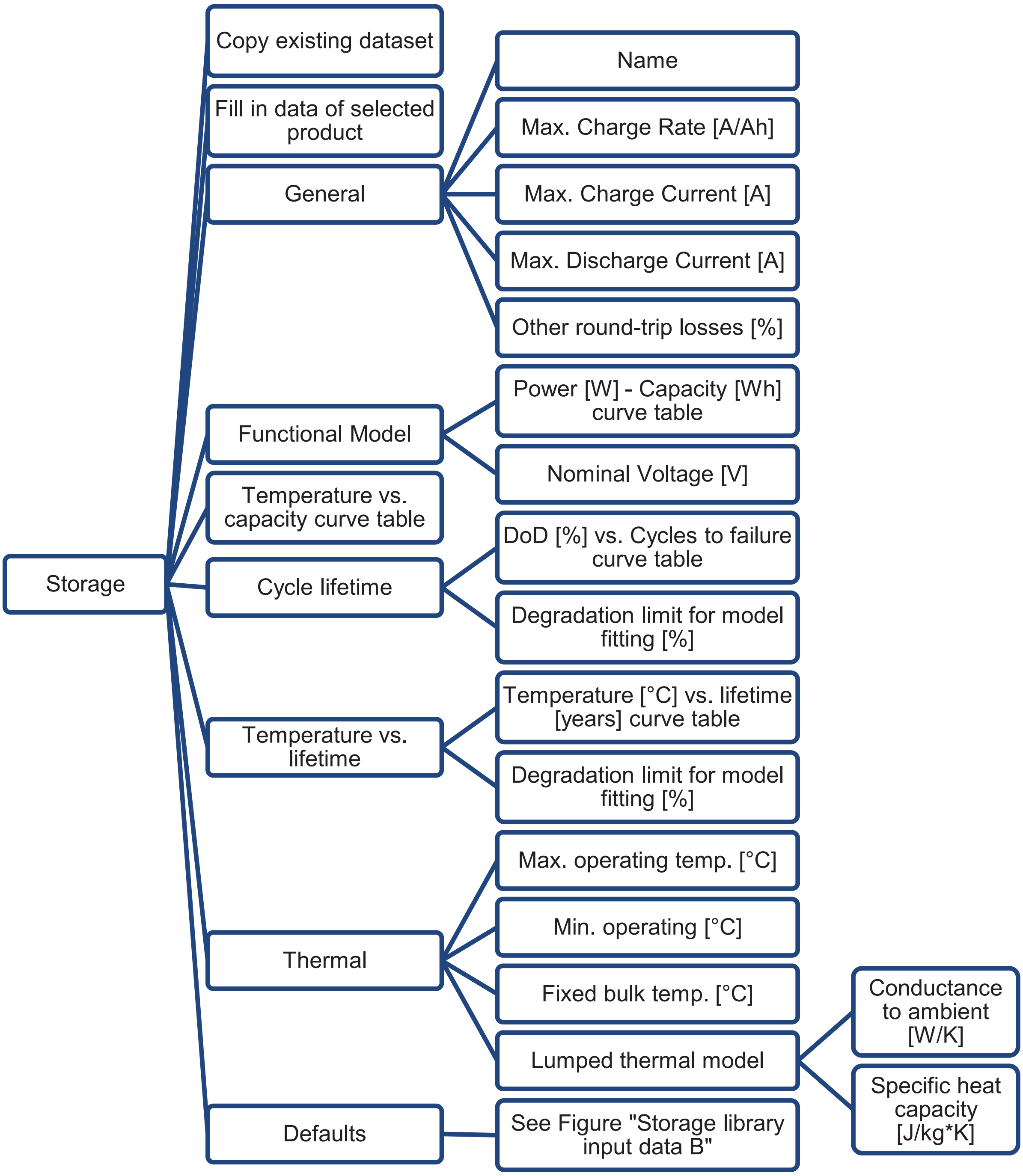
FIGURE 66: GENERATOR LIBRARY INPUT DATA FOR SIMULATION



SOURCE: Homer Energy (2017)

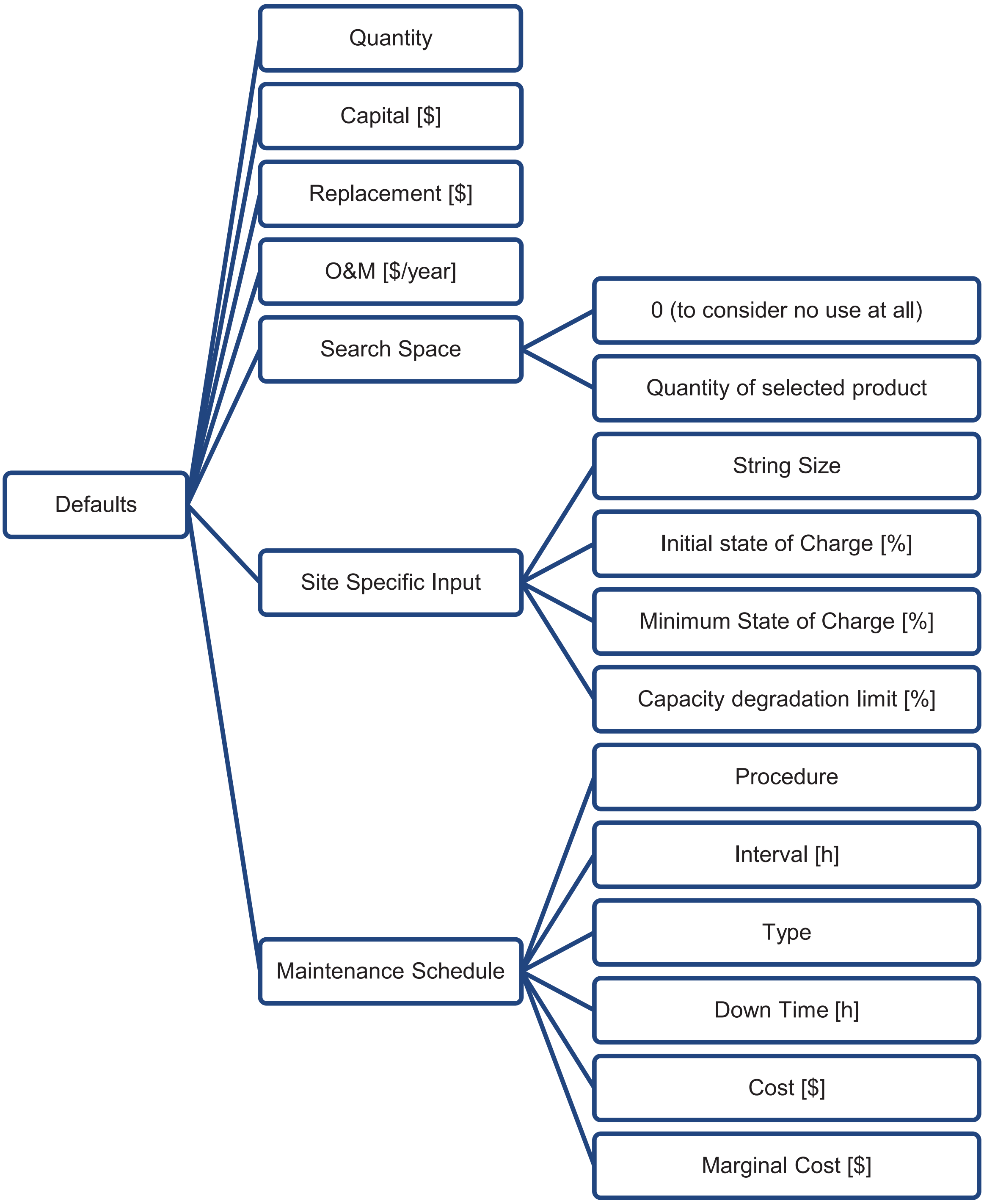
The next component, the storage, must be added to the library the same way. After selection of the desired product, the datasheet from the manufacturer and the local price information are required to fill complete the dataset, as shown in FIGURE 67 and FIGURE 68.

FIGURE 67: STORAGE LIBRARY INPUT DATA A



SOURCE: Homer Energy (2017)

FIGURE 68: STORAGE LIBRARY INPUT DATA B



SOURCE: Homer Energy (2017)

Some of the required technical information is might not be delivered by the manufacturer, in this case a typical value from the literature is selected, compare Chapter 2. To protect the battery system from external influences, an appropriate housing is required. The main characteristics might be protection of the batteries from extreme temperatures, humidity and protection of users from electric dangers.

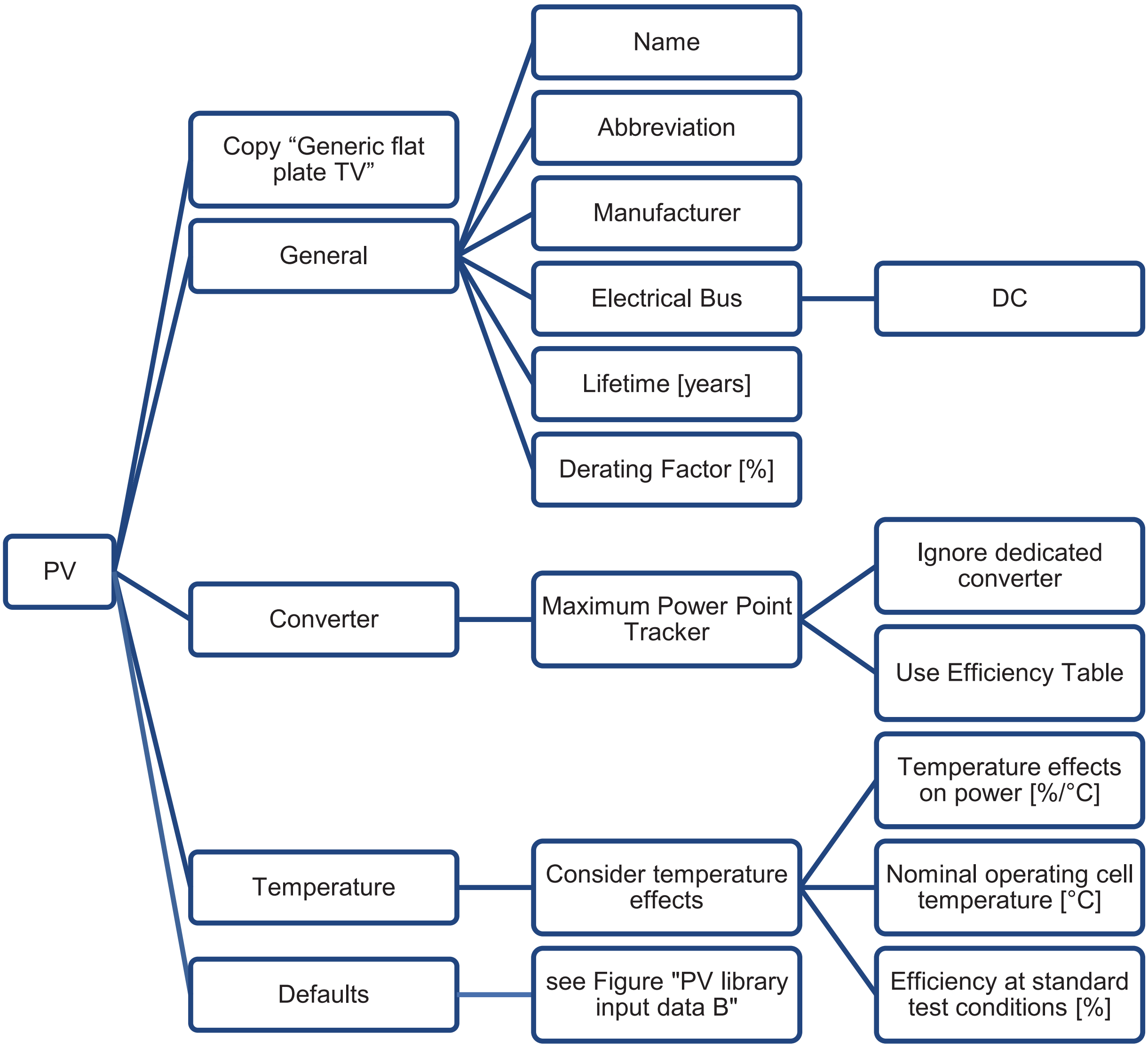
Next component to be added to the library is the PV system. After selection of the desired product the specific data must be filled in to be available for the simulations. As already mentioned, the PV panels also require an own mounting system, which is a free standing, metal structure, which can be build up independent on the existing building structures, see FIGURE 69 as an example.

FIGURE 69: EXEMPLARY PV MOUNTING SYSTEM

SOURCE: Wagner-solar (2017)

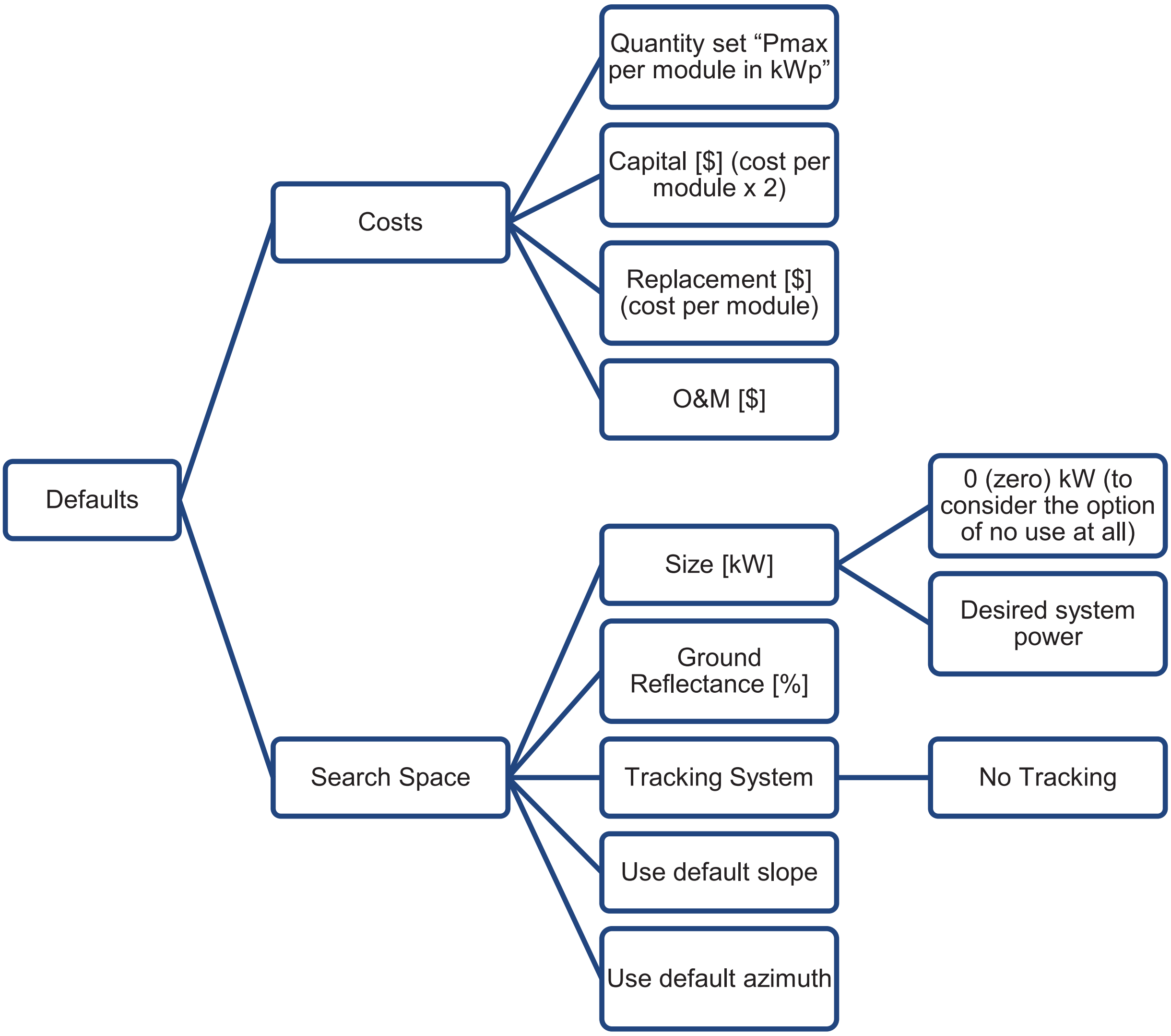
The costs of these mounting systems are included in the investment for PV panel with an additional cost in the amount of 100 % of the PV modules itself. The required information, published by the manufacturer and resellers, is shown step vice in FIGURE 70 and FIGURE 71.

FIGURE 70: PV LIBRARY INPUT DATA A



SOURCE: ‘Homer Energy’ (2017)

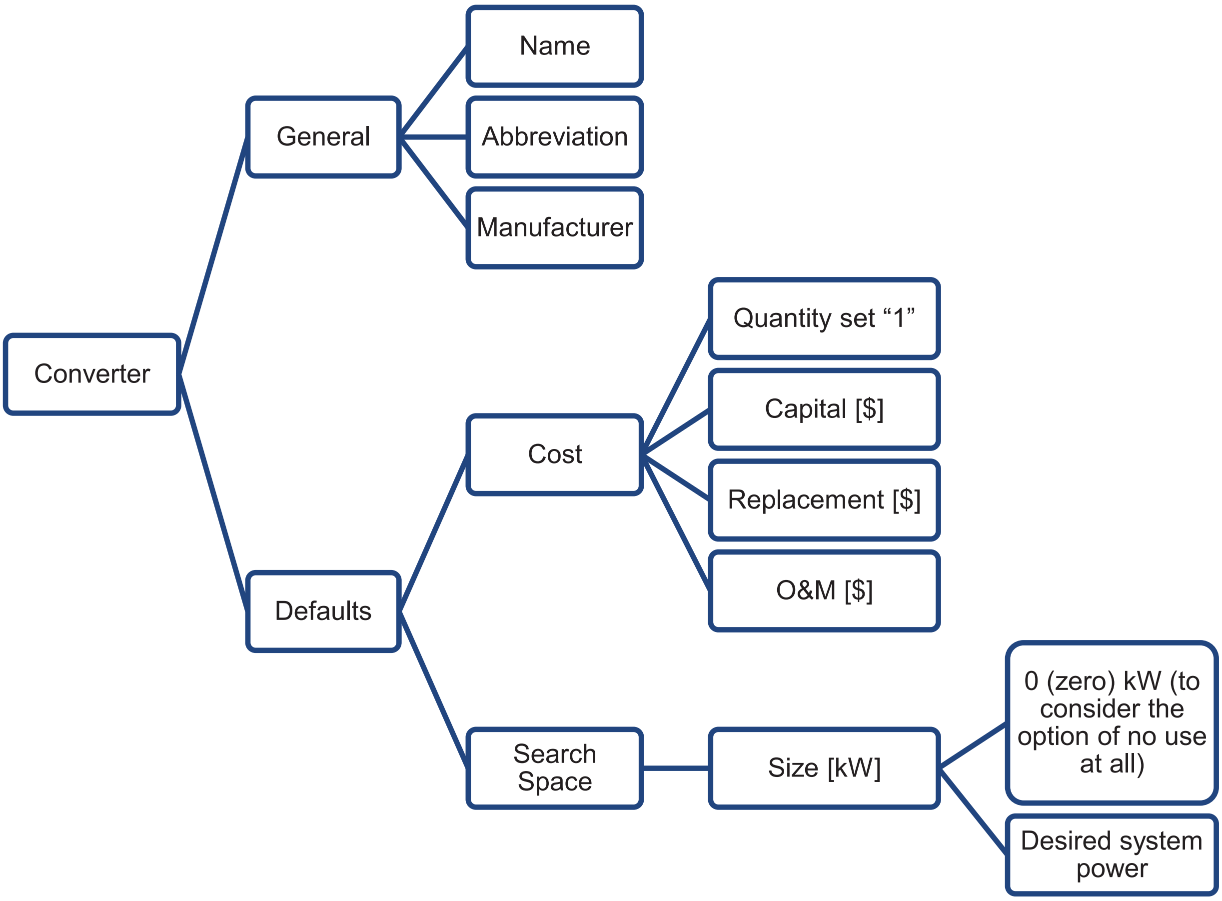
FIGURE 71: PV LIBRARY DATA INPUT B



SOURCE: 'Homer Energy' (2017)

The last component to be added to the library is the converter, which is used for both, PV and battery system operation. Homer energy combines under the component converter the hardware in charge for AC/DC, DC/DC and DC/AC conversion. Therefore, depending on required system components, a dataset of combined technical and economic information must be set up. The input parameters for the converter component are presented in FIGURE 72.

FIGURE 72: CONVERTER LIBRARY INPUT DATA

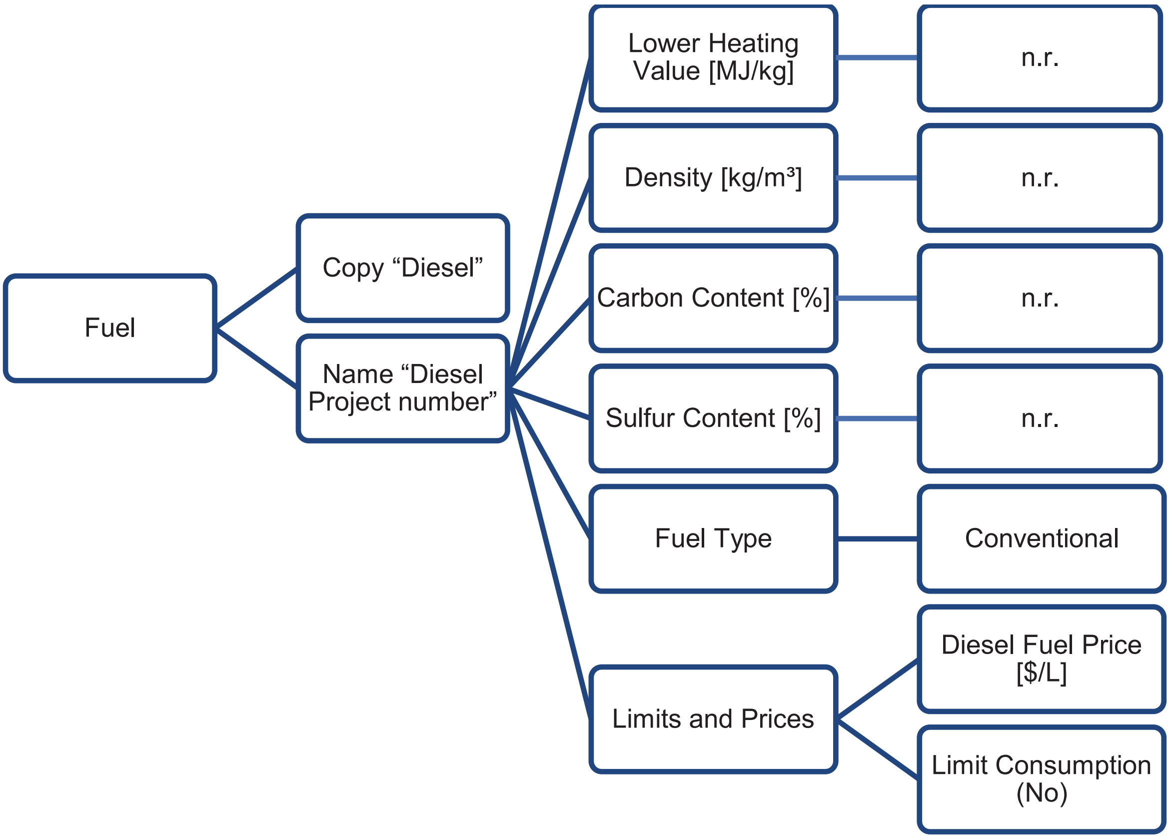


SOURCE: 'Homer Energy' (2017)

After completion of all required system components, the resources have to be added to the library. The resources data includes information about solar radiation, fuel costs, temperature curves and wind speed at the selected system location. Climate data can also be imported directly in the beginning of the project creation as explained before, using the historic data from the NASA, like done in this work.

The fuel costs for diesel generation need to be added. These costs are strongly dependent on the location of final consumption, due to losses and costs of transportation and trading. Since an in-detail analysis of environmental impacts is not part of this work, the composition values of the fuel are not required (n.r.) for the simulations. Orientation for data input for fuel costs and eventual capacity shortages is provided by FIGURE 73.

FIGURE 73: FUEL LIBRARY INPUT DATA



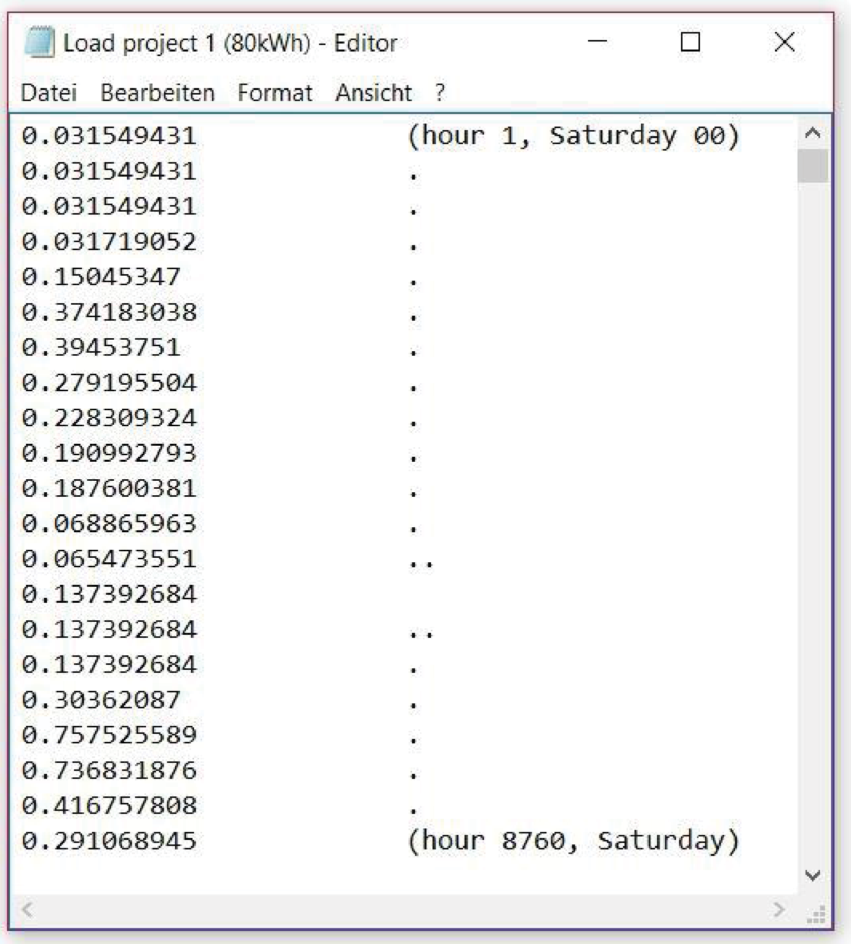
SOURCE: Homer Energy (2017)

System Setup

After adding general information and components to the library, the case specific system data must be added and the components for the desired battery project selected. The remaining data input is done in the “home” view, as explained in detail in this subchapter.

The electric load is characterised by the intended type of service or customer, the battery system is supposed to satisfy. The load curves can be based on real measurements or estimative approaches and need to be prepared in form of a timeline with values for demand in kilowatt in equal steps of time over one year, starting on January the 1st, which is considered as a Saturday. An example for data formation before upload to the library is given in FIGURE 74.

FIGURE 74: ELECTRIC LOAD CURVE UPLOAD EXAMPLE

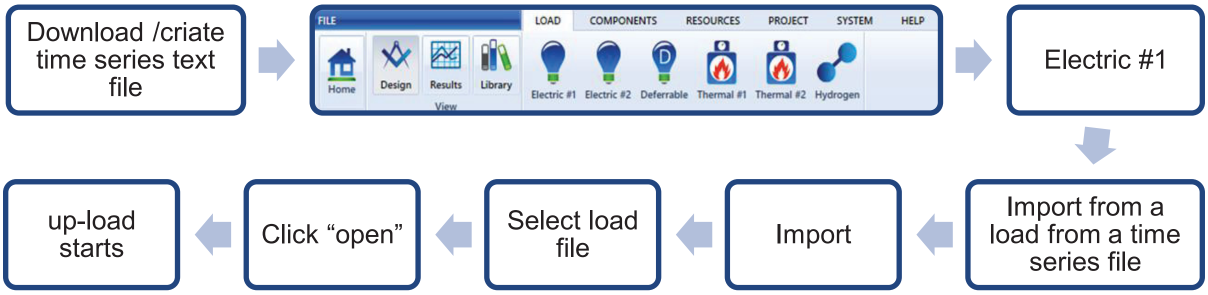


```
0.031549431             (hour 1, Saturday 00)
0.031549431             .
0.031549431             .
0.031719052             .
0.15045347              .
0.374183038             .
0.39453751              .
0.279195504             .
0.228309324             .
0.190992793             .
0.187600381             .
0.068865963             .
0.065473551             ..
0.137392684
0.137392684             ..
0.137392684             .
0.30362087              .
0.757525589             .
0.736831876             .
0.416757808             .
0.291068945             (hour 8760, Saturday)
```

SOURCE: The author

The procedure of electric demand curve upload is shown in FIGURE 75.

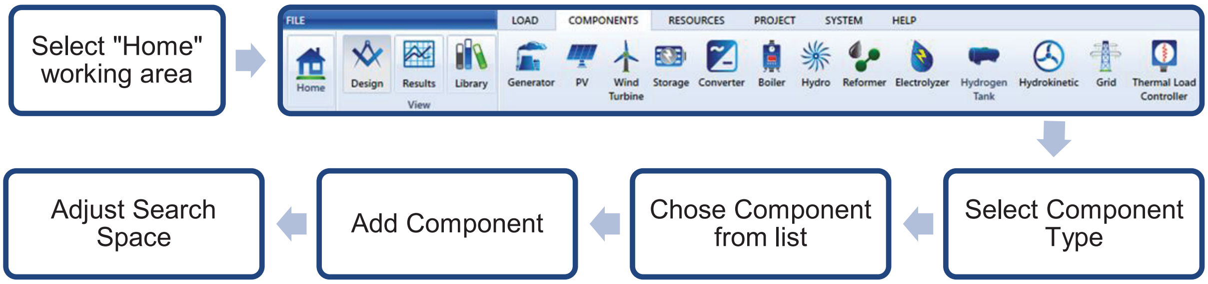
FIGURE 75: ELECTRIC LOAD CURVE IMPORTATION TO SIMULATION PROCESS



SOURCE: Homer Energy (2017)

Once all data are added to the library and load the customer load profile is upload, the system must be mounted. To add components to the system, they are selected one after the other to the project, as shown in FIGURE 76.

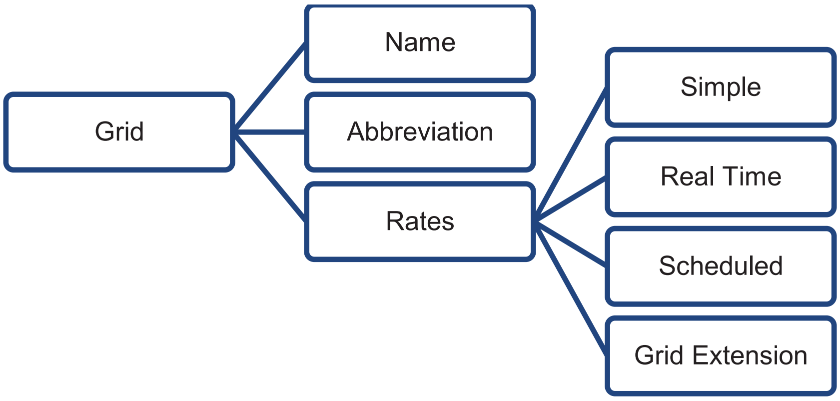
FIGURE 76: MOUNTING OF SIMULATION SYSTEM



SOURCE: Homer Energy (2017)

In case of on-grid systems, in this step also the grid characteristics must be defined. This includes information about capacity, quality and costs. An overview of available grid types is given by FIGURE 77.

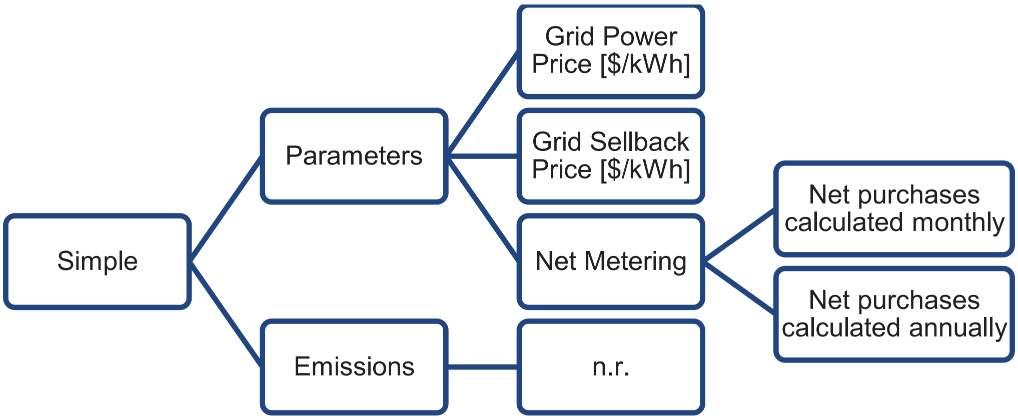
FIGURE 77: GRID TYPES FOR PROJECT SIMULATION DATA INPUT



SOURCE: Homer Energy (2017)

Grid rates need to be informed to the simulation program concerning desired considerations in terms of availability and cost. The respective data input possibilities for the electricity grids are shown in detail in figures 78 to 81, the simple rates are sufficient to consider conventional tariffs with fixed rates for electricity from the distribution network.

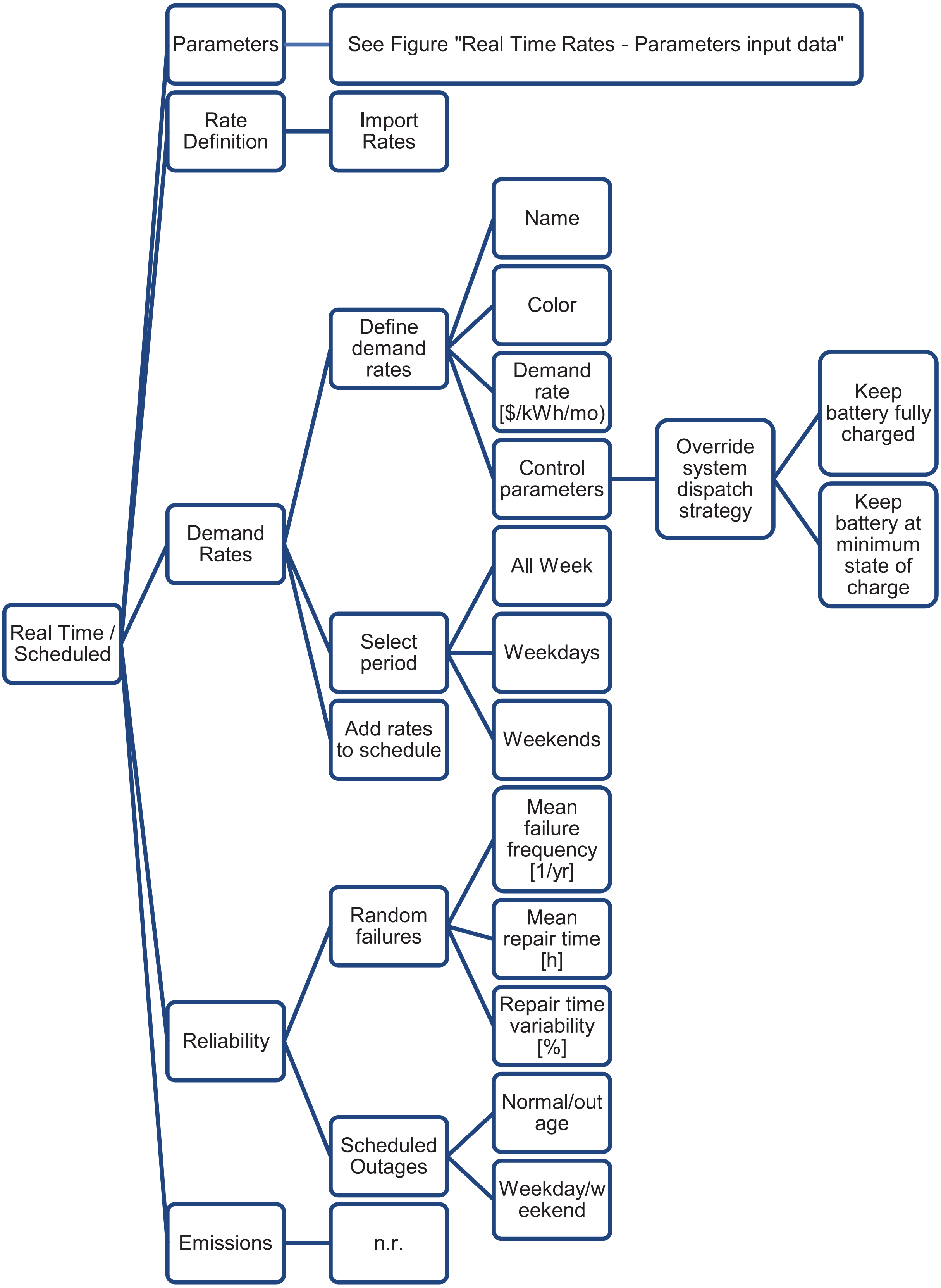
FIGURE 78: GRID - SIMPLE RATES INPUT DATA



SOURCE: Homer Energy (2017)

The simple rates are sufficient to consider conventional tariffs with fixed rates for electricity from the distribution network.

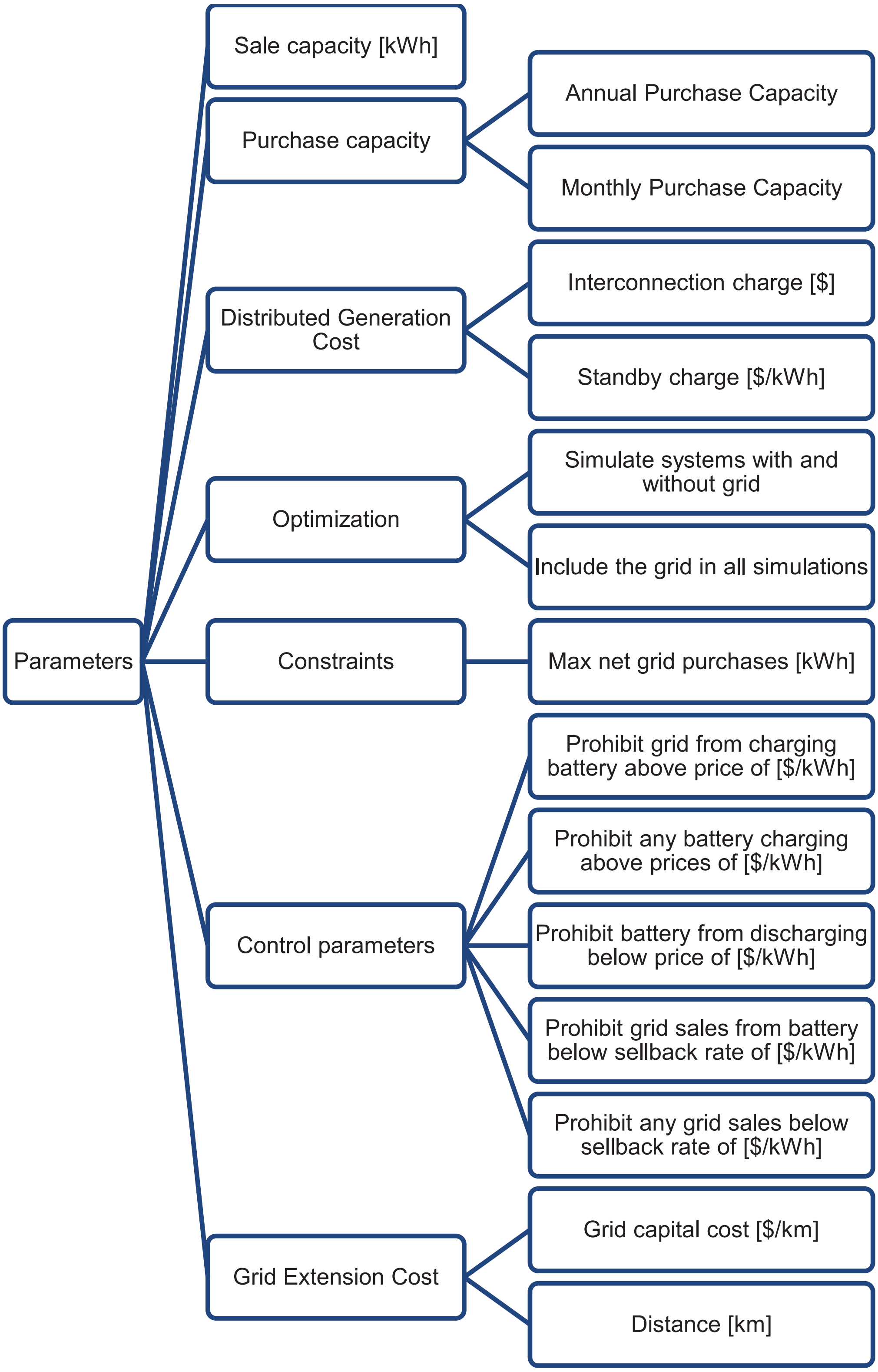
FIGURE 79: REAL TIME RATES INPUT DATA



SOURCE: Homer Energy (2017)

The Scheduled rates offer space for hour-seasonal, time dependent electricity tariffs, which use on and off-peak rates.

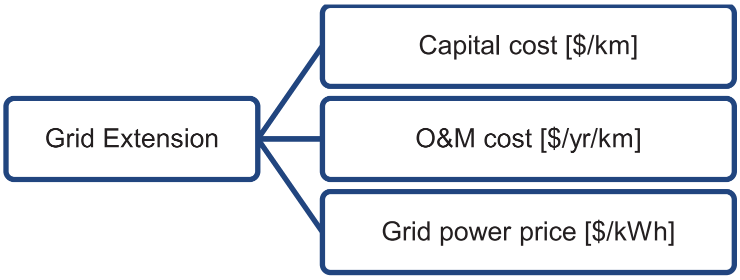
FIGURE 80: REAL TIME RATES - PARAMETERS INPUT DATA



SOURCE: Homer Energy (2017)

The real-time rates require respective electricity price curves for power and sellback, which must be prepared and upload in advance. This is the right choice for white tariff analysis. The grid extension option can be used for comparative investment cost analysis or as part of the desired electrification project and required data input is shown in FIGURE 81.

FIGURE 81: GRID EXTENSION INPUT DATA

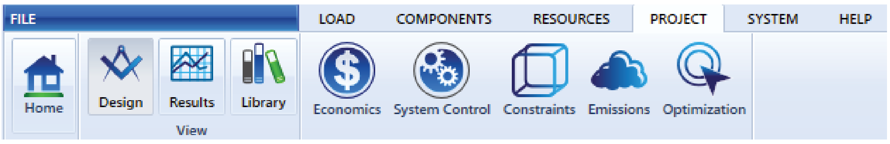


SOURCE: ‘Homer Energy’ (2017)

Definition of framework conditions

The framework conditions include information of the analysis on business model, project environment, electricity market and ESS hardware, which is not jet inserted to the simulation program during the previous steps. This includes further settings on economics, constraints of system operation and optimizations and can be accessed as indicated in FIGURE 82.

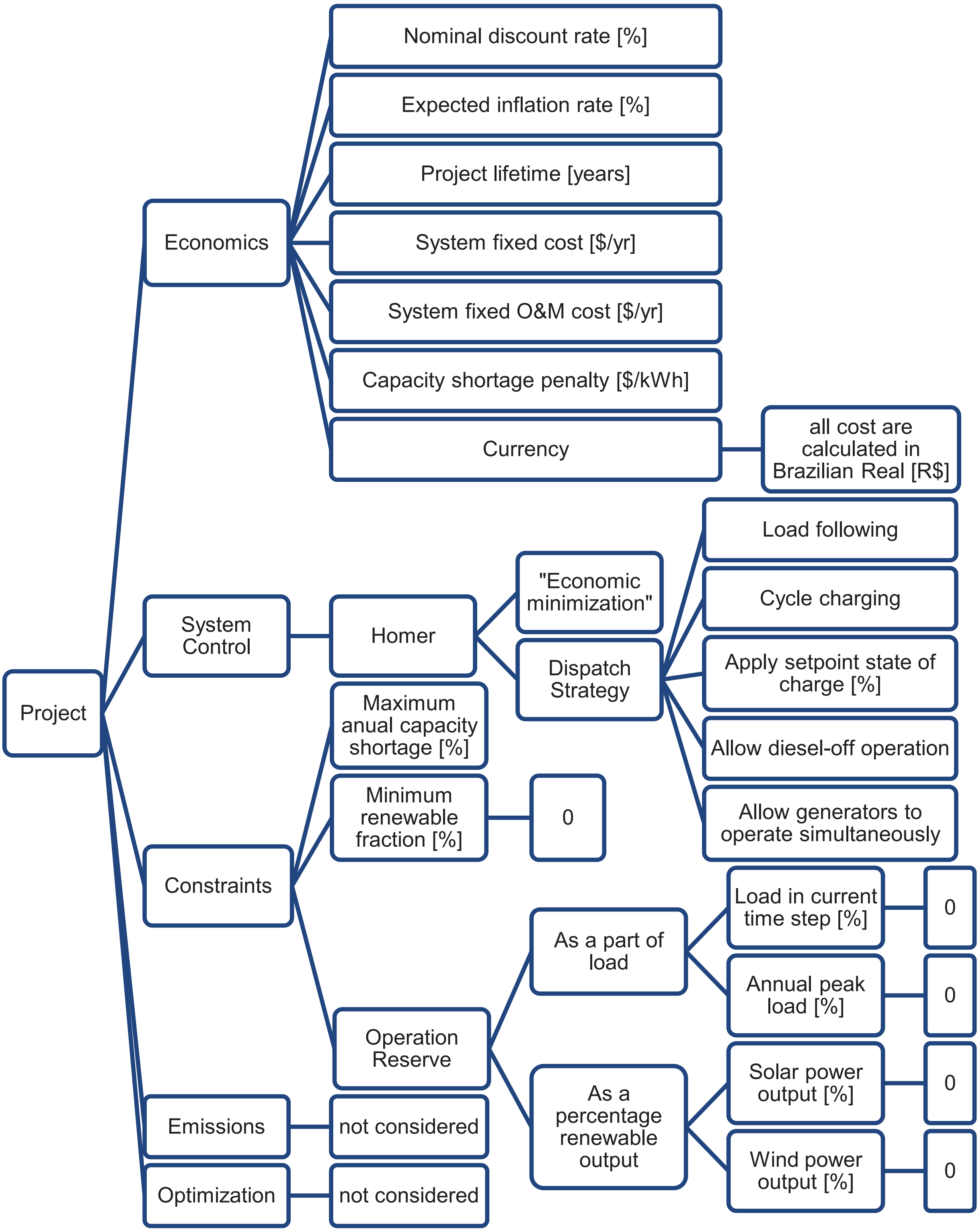
FIGURE 82: PROJECT SETTINGS



SOURCE: Homer Energy (2017)

The available settings are shown in FIGURE 83 and must be selected individually for all projects in alignment with the specific conditions.

FIGURE 83: PROJECT SETTINGS AVAILABLE CRITERIA

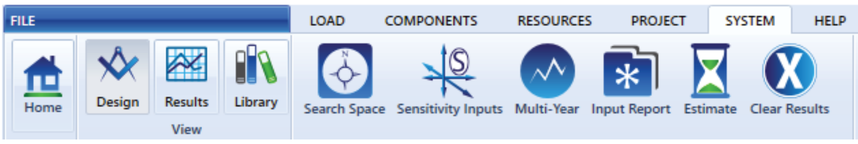


SOURCE: Homer Energy (2017)

Execution of simulations

Once all relevant information is fed into the simulation program, the calculations are executed. To control all hardware component combinations, the search space can be utilized, see FIGURE 84, which lists all selected hardware components and the possible quantity of utilization in terms to find the most suitable overall solution.

FIGURE 84: METHOD - ANALYSIS OF RESULTS AND OPTIMIZATION



SOURCE: Homer Energy (2017)

To get an overview of the selected sensitivity inputs, which are available for certain parameters, such as economics, see FIGURE 83, or demand curves, the sensitivity input window can be used, see also FIGURE 84.

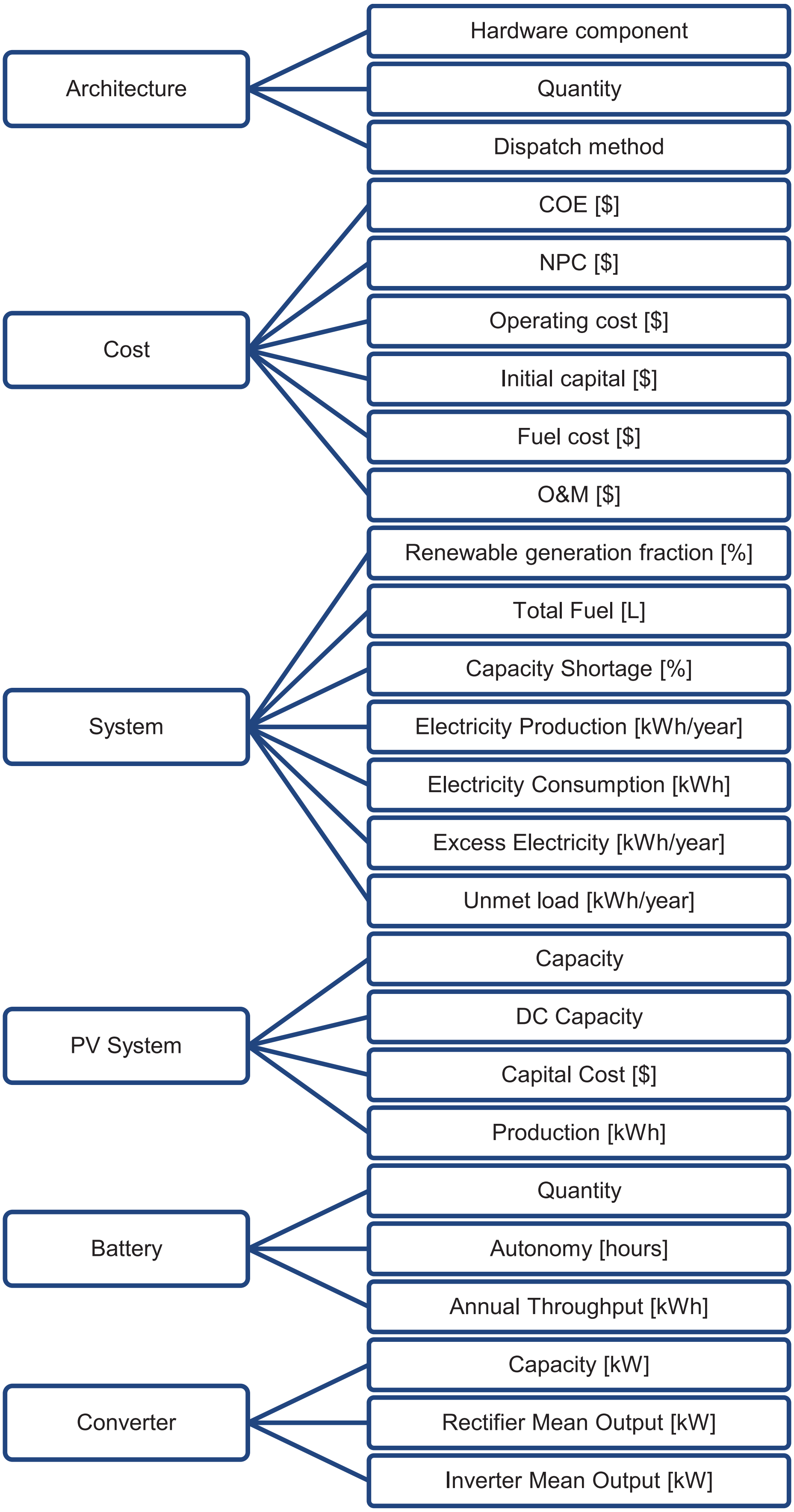
The option Multi-Year can be used to consider variations on system fixed O&M cost, PV-system degradation rate, Fuel prices or electric loads, between different years of operation. A multiplication factor can be used to manipulate the base year value for each operation year.

The Input Report option can also be used to control all input data in one document, without need to jump between different program windows. The Estimate button informs about the number of simulations to be realized, under consideration of the current data input, the required calculation time, the number of optimization cases and sensitivity cases. The Clear Result button is not necessarily to be used, since the program starts new calculations even without clearing of the old once.

Analysis of results and optimization

After calculation, the results are listed chronologically, starting with the most suitable, in relation to the selected optimization criteria. The results can be further analysed as a whole set of system constellations or in sub groups, by filtering the dataset of results by any of the parameters, presented in FIGURE 85.

FIGURE 85: SIMULATION RESULTS OPTIMIZATION CASES



SOURCE: Homer Energy (2017)

As soon as a specific solution is pre-selected, the detailed analysis of techno-economic performance is carried out. The Whole analysis of results offers information about

- Cost summary
- Cash flow
- Electrical
- Renewable Penetration
- System components
- Emissions

Depending on the project target an intensive analysis of specific technical, operational or economic parameters is done.

Simulation of conventional alternative

To analyse the viability of the selected battery system, a comparison with conventional solutions is necessary. The conventional alternative off course depends on the studied problem, service or application. But generally, include grid extension or reinforcement, fossil fuel generators, demand control, generation dispatch or alternative storage technologies.

To guarantee comparable results, the utilized conventional alternative needs to fulfil the same performance quality, even if the calculations are kept in a simplified way in this work, since the focus is on distributed battery system utilization.

Comparison of results and conclusions

As a final step the results of the battery system are compared with the conventional solution, to see the advantages and disadvantages of both solutions and identify critical parameters and characteristics, making each option the more convenient or unsuitable one.

5 SIMULATIONS AND RESULTS

This chapter presents the roadmap for distributed battery storage systems in Brazil for the next four years, based on the results of the R&D program *Chamada 21*. A classification of all distributed battery projects into six groups is made in terms of technologies and applications. One project proposal of each is then selected to execute techno-economic calculations with the smart grid simulation program Homer Energy. The results of simulation are further compared, in terms of costs, with alternative solutions, which do not use battery systems. In the end of this chapter the results are analysed and compared with the literature and discussed regarding to reliability and representability for other systems and applications of this type.

5.1 R&D - ROADMAP FOR ESS IN BRAZIL

Anchored in the law n° 9.991/2000 determines that concessionaires, permissionaires and authorized companies of the electricity sector are obliged to apply a percentage of their Net Operating Revenue (NOR) in research and development (R&D) annually. 40 % of these funds are destined for projects as defined by the regulatory of the national agency for electric energy "*Agência Nacional de Energia Elétrica*" (ANEEL). ANEEL defines topics and publishes calls for proposals from paying institutions, what allows them to spend this money on research and development projects which are also in their own interest. The whole process and regulations are published at the homepage of ANEEL and can be accessed at 'ANEEL R&D - lei nº 9.991/2000' (2017). The latest call for project proposals, *Chamada 21* – "*Arranjos Técnicos e Comerciais para a Inserção de Sistemas de Armazenamento de Energia no Setor Elétrico Brasileiro*" from 2016, see ANEEL (2016), is dedicated to technical and commercial arrangements for energy storage systems for the Brazilian electricity sector.

There were 29 project proposals presented by 19 institutions, treating the theoretical study and implementation of 13 different ESS technologies in a wide field of 25 application types planned to be elaborated during the next four years. The projects represent a total of 70 to 80 pilot plants in a capacity range from 2 kWh until 120 MWh, an aggregated investment volume of over R$ 500 million, involving 44 companies and 26 universities and research institutions.

Based on data selected during the presentation weak at ANEEL in Brasília a mapping of the national R&D activities and actors has been elaborated including information about storage technologies, applications, involved companies, universities and research institutions and investment volumes. The main results are presented in this chapter and represent in line with the literature review the justification of selected technologies and applications for the simulations carried out in this thesis.

From the 63 different proposed systems, 56 are working with batteries, 43 with batteries and PV modules, whereof 29 are isolated, three systems are working connected to wind turbines, one of these in combination with a compressed air energy storage and two with a battery and five projects are working with a battery combined with PV and diesel generator.

An overview of all proposed storage systems, divided by technology type, storage capacity and voltage level are given in TABLE 26.

TABLE 26: ESS TECHNOLOGIES PROPOSED IN *CHAMADA 21*

Technology	**Quantity of systems and voltage level**					**Capacity [kWh] of systems in voltage level**				
	total	**LV**	**MV**	**HV**	**Isolated**	**total**	**LV**	**MV**	**HV**	**Isolated**
Battery	15	5	7	2	1	5,730	155	3,575	2,000	
Battery (advanced lead acid)	1		1			1,000		1,000		
Battery (used)	1									
CAES	1			1		120,000			120,000	
Li-ion	8	5	3		5	2,253	183	2,070		693
Li-ion iron phosphate (LFP)	1		1			2,000		2,000		
Li-ion / lead acid	1	1								
OPzS	10	10			10	151	151			151
P2G2P H2 + FC	2		2			1,100		1,100		
Advanced lead acid	11	11			11	79	79			79
Sodium	2	2			1					
Sodium-Nickel	1	1				18	18			
Pumped hydro power	4		1	3		1,000		1,000		
VRF	3	1	2		2	2,000		2,000		1,000
Not known	2									
Sum	**63**	**36**	**17**	**6**	**30**	**135,330**	**585**	**12,745**	**122,000**	**1,922**
Percentage	**100**	**57**	**27**	**10**	**48**	**100**	**0**	**9**	**90**	**1**

SOURCE: The author

As shown in TABLE 26, 89 % of the proposed projects are working with battery technologies representing 8 % of the total proposed installed capacity which is about 13,230 kWh. This indicates that large scale storage projects are expected to continue with pumped hydro and compressed air energy storage technologies, but batteries are expected to cover a wide field of small and medium sized applications in the Brazilian power system.

Out of these remaining proposals 27 %, representing 43 % in terms of capacity, are still undecided in terms of which battery type to use. Lead Acid (LA) batteries show the best popularity with a proposed use rate of nearly 20 % and 79 kWh for advanced LA batteries and 18 %, summing up to 1 % of total proposed capacity, for Long life flooded tubular plate (OPzS) batteries. This shows a tendency for LA batteries in small scale applications. Lithium-ion batteries represented a share of 16 % in number and 32 % in capacity, where 1 single project planes to work with li-ion iron phosphate (LFP), contributing nearly half of the capacity share with a planned size of 2,000 kWh.

The contribution of battery ESS applications, classified by voltage level of operation, grid connection or isolated (isol.) and information about connected generators is shown in TABLE 27 in terms of number of proposed prototype systems and in TABLE 28 as percentage respectively.

TABLE 27: PROPOSED ESS TECHNOLOGIES FOR PROTOTYPES AND VOLTAGE LEVEL OF INSTALLATIONS IN QUANTITY

Battery type	**Quantity of systems and voltage level**					**System combined with PV**					**System combined with diesel generator**				
	total	**LV**	**MV**	**HV**	**Isol.**	**total**	**LV**	**MV**	**HV**	**Isol.**	**total**	**LV**	**MV**	**HV**	**Isol.**
Battery	16	5	7	2	1	12	5	4	1	1	2	1	1		1
Li-ion	10	6	4		5	8	6	2		5	2	1	1		2
OPzS	10	10			10	10	10			10					
Adv. LA	12	11	1		11	11	11			11					
Sodium	3	3			1	2	2								
VRF	3	1	2		2	2	1	1		2	1		1		1
Sum	**53**	**35**	**13**	**2**	**30**	**45**	**35**	**7**	**1**	**29**	**5**	**2**	**3**		**4**

SOURCE: The author

Some classifications are grouped by the author and the differences between the sum of all single voltage levels and the values in “total” of ESS installation is originated in proposals without information about the proposed voltage level and information not available to the author.

TABLE 28: PROPOSED ESS TECHNOLOGIES FOR PROTOTYPES AND VOLTAGE LEVEL OF INSTALLATIONS IN PERCENTAGE

Battery type	**Quantity of systems and voltage level**				**System combined with PV**				**System combined with diesel generator**			
	LV	**MV**	**HV**	**Isolated**	**LV**	**MV**	**HV**	**Isolated**	**LV**	**MV**	**HV**	**Isolated**
Battery	31	44	13	6	42	33	8	8	50	50		50
Li-ion	60	40		50	75	25		63	50	50		100
OPzS	100			100	100			100				
Adv. LA	92	8		92	100			100				
Sodium	100			33	100							
VRF	33	67		67	50	50		100		100		100
Sum [%]	**66**	**25**	**4**	**57**	**78**	**16**	**2**	**64**	**40**	**60**		**80**

SOURCE: The author

First observation is the strict combination of batteries with PV systems in case of all low voltage (LV) isolated projects. OPzS, advanced LA and Sodium batteries in combination with PV are only proposed for low voltage applications, whereby advanced LA batteries in MV level are not related to renewable generators. Combinations with diesel generators are relatively rare but proposed for on- and off-grid applications in low and medium volt levels and in combination with Li-ion, VRF and undefined battery technologies. An overview of proposed applications for battery systems is provided in TABLE 29.

TABLE 29: OVERVIEW OF ESS TYPES, APPLICATIONS, VOLTAGE LEVEL AND SYSTEM COMPONENTS

energy quality	Integration of pv generation	Increase hours of electricity access	Isolated battery + pv system (residential)	peak hours and peak demand response	Integration of renewable generation	Investment postponement	arbitrage	energy efficiency	Integration of electric vehicles	optimization of diesel generation	seasonal reserve (base load)	auxiliary services	Compensation of hydroelectric plant self-consumption with pv	Consumidores criticos / qualidade de energia elétrica	Scheduled contingencies / shutdowns	Scheduled contingencies / back up	1ary 2ary 3ary control	Intentional islanding	PV self-consumption	Regulate seasonal fluctuations in supply and prices	strategic reserve	start up (black start)	quantity of applications	on-grid / mobile / off-grid	Capacity [kWh]	Voltage level	ESS
■					■																		2	on	n.a.	MV/HV	Rev. Hy.P.
													■										4	off	n.a.	LV	Li-ion
													■										4	off	n.a.	LV	Sodium
■	■			■						■													1	off	n.a.	LV	Adv. LA
■	■			■						■													3	off	n.a.	LV	VRF
									■														3	off	n.a.	LV	battery
■				■				■															3	off	510.00	MV	Li-Ion
■	■	■																					3	off	1,000.00	MV	VRF
■	■	■																					3	off	1.68	LV	Adv. LA
■	■	■																					3	off	1.68	LV	Adv. LA
■	■	■																					5	off	2.40	LV	OPzS
	■	■								■													5	off	2.40	LV	OPzS
■	■					■		■	■														4	off	3.36	LV	Adv. LA
■	■							■	■									■					4	off	6.00	LV	OPzS
	■			■			■											■					2	off	11.52	LV	Adv. LA
	■						■									■							0	off	8.40	LV	OPzS
■					■																		4	off	6.72	LV	Adv. LA
																							n.a.	off	6.72	LV	Adv. LA
■	■	■	■																				4	off	6.72	LV	Adv. LA
■	■	■	■																				4	off	6.50	LV	Li-Ion
■	■	■	■																				4	off	12.00	LV	OPzS
■	■	■	■																				4	off	12.00	LV	OPzS
■	■	■	■																				4	off	12.00	LV	OPzS
■	■	■	■																				4	off	24.00	LV	OPzS
■	■	■	■																				4	off	24.00	LV	OPzS
■	■	■	■																				4	off	13.44	LV	Adv. LA
■	■	■	■																				4	off	13.44	LV	Adv. LA
■	■	■	■																				4	off	13.44	LV	Adv. LA
■	■	■	■																				4	off	48.00	LV	OPzS
■	■	■	■																				4	off	26.00	LV	Li-Ion
■	■	■	■																				4	off	150.00	LV	Li-ion
■	■	■	■																				4	mobile	2,000.00	MV	LFP
■	■	■	■																				4	mobile	1,000.00	MV	battery
■	■	■	■																				4	n.a.	n.a.	n.a.	x
■	■	■	■																				4	n.a.	n.a.	n.a.	x
■	■	■	■																				4	on	500.00	MV	battery
■	■	■	■																				4	on	1,100.00	MV	P2G2P H2+FC
■	■	■	■																				4	on	n.a.	LV	Li-Ion or LA
■	■	■	■																				3	on	1,000.00	MV	battery
■	■	■	■																				3	on	1,000.00	MV/HV	battery
	■			■								■											3	on	75.00	LV/MV	battery
	■			■								■											3	on	5.00	LV	battery
	■			■								■											4	on	n.a.	MV	battery
	■			■								■											3	on	1,000.00	MV/HV	battery
■				■	■															■			4	on	1,000.00	MV	battery
■											■						■						3	on	50.00	LV	battery
■											■						■				■		0	on	50.00	LV	battery
	■			■		■																	4	on	50.00	LV	battery
																							n.a.	on	120,000.00	MV/HV	CAES
■							■									■							4	on	n.a.	MV	battery
				■																			1	on	n.a.	MV	P2G2P H2+FC
■				■							■				■								1	on	n.a.	yes	battery 2nd life
											■												4	on	n.a.	yes	battery
					■																		4	on	1,000.00	MV	baterry (adv. LA)
■	■			■		■																	4	on	n.a.	MV/HV	Rev. Hy.P.
■					■	■								■									1	on	1,000.00	MV	Rev. Hy.P.
■					■	■								■									2	on	560.00	LV/MV	Li-ion
									■														3	on	1,000.00	MV	Li-ion
			■																■				3	on	1,000.00	MV	VRF
■				■										■								3	on	n.a.	LV	Sodium
	■									■												■	1	on	n.a.	LV	Li-ion
■	■						■																1	on	n.a.	MV/HV	Rev. Hy.P.
								■															1	on	18.00	LV	Sodium-Nickel
43	**41**	**27**	**23**	**14**	**6**	**5**	**4**	**4**	**4**	**4**	**4**	**4**	**2**	**2**	**2**	**2**	**2**	**2**	**1**	**1**	**1**	**1**			**135,330.42**		**Sum**

SOURCE: The author

Even if there are several applications under multiple system constellations planned to be realized by the national R&D forces during the ongoing four years, some tendencies can be observed. A general observation is the multiple utilization purpose of ESSs with up to five application types for the same equipment.

Most obvious applications for isolated battery systems on low voltage level are integration of PV, rising the number of electricity access and so also energy quality with focus on single residential electrification or distant areas with access complications, like islands, forests or marshlands.

On-Grid applications on LV level are mainly focussed on PV integration and demand and generation peak shaving, followed by ancillary services, to name only the most relevant in number.

On MV level storage capacity raises considerable to about 1 MWh in most proposals. Also, the use face changes its focus, being on energy quality, in combinations with energy efficiency, optimization of diesel generators, PV integration, investment postponement, peak shaving and arbitrage activities, intentional islanding or critical customer services.

There are also mobile battery systems proposed to be developed, which are expected to run on MV level to serve the same needs as stationary ESSs but with the aim on energy quality services on scheduled events, such as seasonal peak demands, scheduled shut downs.

Based on the total data base of proposed projects with various ESS technologies, applications and system structures, the following system combinations, as summed up in TABLE 30, are formed to represent the ongoing R&D efforts on distributed ESSs in Brazil.

TABLE 30: ROADMAP FOR R&D ON ESS TECHNOLOGIES, CHARACTERISTICS, SYSTEM STRUCTURES AND APPLICATIONS

N°	ESS	Grid	Voltage level	Capacity [kWh]	PV [kWp]	Diesel generator	Applications
1	Li-ion, LA, OPzS	Off	LV	<150	<30	optional	Rural, residential PV + battery electrification
2	Li-ion, VRF	Off	MV	500 - 1,000	<1,000	yes	Optimization of PV and diesel generators, electricity quality and peak shaving
3	Li-ion, LA, VRF, Sodium	On	LV	<50	<50	optional	Residential PV + battery system, peak shaving, electric vehicle integration
4	Li-ion, LA, VRF, Sodium	On	LV/MV	50 - 500	<200	no	Smart grid simulation, energy quality and efficiency improvement, renewable generation integration
5	Li-ion, adv. LA, LFP, VRF	On	MV	500 - 1000	optional	optional	Energy quality, PV integration or self-consumption, (seasonal) demand and generation peak shaving, grid maintenance, EV integration
6	Li-ion, LA VRF, Sodium	On	MV/HV	1,000	optional	no	Energy quality, RE and EV integration

SOURCE: The author

ESS classification description:

1. First case for rural or small island electrification, based on single houses without interconnection with other consumers. The variety of outlying locations within the Brazilian territories is great and reaches from the Amazonas rain forest and the Pantanal marshlands until real islands spread around the Atlantic coast line.
2. Second case represents also islanded locations, without transmission grid connection but consisting of various consumers, being interconnected with a low to medium voltage distribution grid and centralized PV and or diesel generators.

3. Third case is defined by a residential, low voltage and on grid utilization of small scale battery systems in combination with decentralized, on roof PV generation. Motivations of use of a battery system can be the optimization of PV self-consumption as well as grid injection in respect to peak demand and load but also the integration of EV charging.
4. Case four stands for the utilization of medium scale, centralized or commercial, consumer owned battery systems connected to the low to medium voltage grid and or substations to improve electricity quality and efficiency, subdue fluctuations and peaks of renewable generation on low voltage distribution level.
5. Fifth ESS utilization case is characterised by a centralized, medium voltage, on grid operation of major, medium scale storage systems, which can be direct or indirect related to decentralized renewable or traditional generators. Focus of utilization is on energy quality, whereby motivation of operation varies from fluctuating injection of renewable generation sources, seasonal or specific event based demands, end of line voltage irregularities, support of EV charging or even scheduled grid disconnections, back up supply or commercial scale PV self-consumption.
6. Case number six is defined by centralized medium to large scale ESS utilization connected to medium to high voltage grid or substations for electricity quality services.

5.2 SIMULATIONS - PROJECT SELECTION AND GENERAL SETTINGS

To cover the whole field of R&D, one project from each of the six classification groups is selected to perform a techno-economic analysis with Homer Energy smart grid simulation program. An overview of the main characteristics of the selected systems is given in TABLE 31.

TABLE 31: SELECTED ESS PROJECT CHARACTERISTICS FOR TECHNO-ECONOMIC SIMULATIONS WITH HOMER ENERGY

N°	ESS	Cap. [kWh]	Power [kW]	Volt. - level	Grid	FV [kWp]	Diesel gen. [kW]	Application
1	OPzS LC	10	1.2	LV	off	1.2	None	Rural, residential electrification with PV-battery systems.
2	Li-ion	1510	950	MV	off	950	3,692	Diesel consumption minimization, PV integration
3	Li-ion	10	3	LV	On	2.4	None	Residential PV-battery system for electricity cost minimization under white tariff application
4	Li-ion	50	50	MV	On	37	None	Commercial PV-battery operation for cost minimization and peak shaving
5	Li-ion	1,000	500	MV	On	500	None	Large scale PV integration (smoothing) under grid capacity limitations
6	VRF	2,000	500	MV	On	None	None	Electric energy quality,

SOURCE: The author

System 1 is characterized using an OPzS or lead carbon battery in combination with PV generation for a rural, off-grid, residential electrification in the Pantanal region. The average monthly electricity consumption is considered with 80 kWh per consumer. The load curve, used for system dimensioning and simulations, is based on the outcomes of a field study on consumer electricity demand, curried out as part of a former R&D project at Institutos Lactec.

Project 2 simulates the utilization of a 1,510 kWh li-ion battery system as part of an isolated micro grid, operated in MV level and supplying about 934 consumer units. The battery is expected to improve the energy quality under combined PV and reduce the diesel generation.

System 3 shows a residential consumer, connected to the low voltage distribution grid and owner of a PV-battery system in an urban region is analysed. Utilization of a lithium-ion battery with a storage capacity of about 10 kWh and a 2.4 kWp PV system in combination with a monthly consumption of 250 kWh or 500 kWh and white tariff conditions. The battery system is used to shift the PV production capacity from the off-peak to the on-peak hours. This way high electricity rates for the consumer and renewable generation peaks as well as demand peaks during on-peak hours are avoided.

System 4 is a commercial consumer, connected to the medium voltage distribution grid in an urban region is analysed. A generic lithium-ion battery with a storage capacity of about 50 kWh, in combination with an average daily consumption of 500 kWh and conventional, blue and green tariff conditions is analysed. The battery system is used to shift the PV production of a 37 kWp installation from the off-peak to the on-peak hours. This way high electricity rates for the consumer and renewable generation peaks as well as demand peaks during on-peak hours are tried to be avoided.

System 5 simulates a 1,000 kWh and 500 kW lithium ion battery system, used to smoothen the fluctuating and maximal generation peaks of a 500 kWp PV plant, under distribution network capacity limitations. The Storage device is located next to the PV plant, which is on the endpoint of a large medium voltage line and cloth to a transformer point to the low voltage level. The distribution grid operator applies the battery to compensate the electricity quality problems for the low voltage consumers, caused by the PV plant by limiting and smoothening the generation.

System 6 shows the application of a Vanadium Redox Flow (FRV) battery system, connected to the middle voltage distribution grid with energy quality and availability problems during electricity system critical peak hours. These system critical peak hours are based on overload of distributed feeders, caused by elevated temperatures. If there is no distributed generation available, to compensate the local capacity losses, the feeders need to be switched off. The integration of a Battery system is analysed, to guaranty electricity supply and avoid penalty fees for the distribution grid operators, which vary in relation to the duration of the power cut and the quantity and type of affected consumers.

First, general settings for all simulations must be done. These are based on historical data and expectations of the economic environment and observed technology. Selected criteria and values are the following:

- Inflation rate
    - The inflation rate is considered with 6 %, based on the Brazilian average value from 2008 until 2017, as published by ‘Global-Rates.com’ (2017).

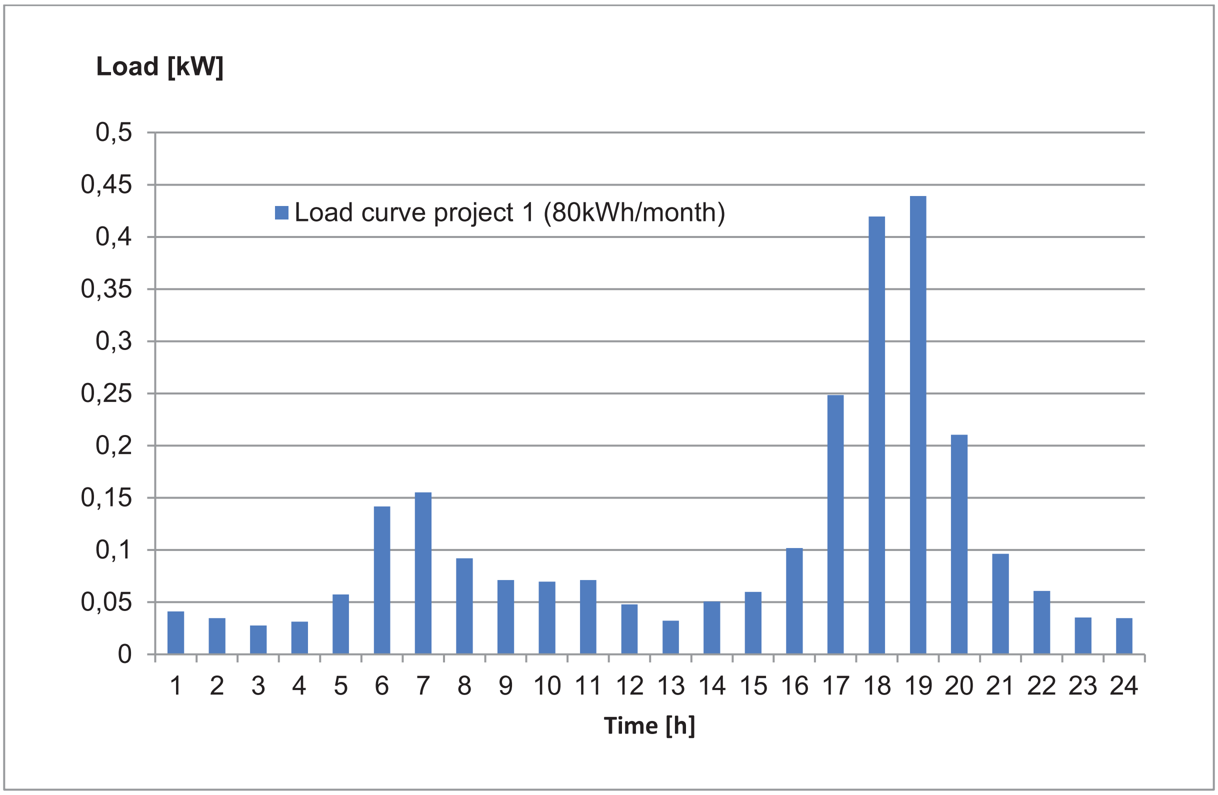
- Project lifetime
    - Project lifetime is set with 20 years, a time horizon which is also used for PV modules which are considered as long-life products with low failure rates and therefore an orientation for overall system life. The time span is also long enough to consider the impacts of reinvestments for failing system components. But still the time is not as long as compared to conventional investment projects from the electricity sector, because of the young and dynamic market for distributed battery systems in Brazil and ongoing advances in technology and economics.
- Discount rate
    - The discount rate is used to calculate the net present value of all the system, taking into consideration the moment of occurrence. As it represents somehow the expected revenue of an investment the chosen value is based on individual, company internal calculations. In this work a value of 12 % is used as indicated by the Brazilian central bank, see bcb (2017).
    - All component lifetimes are considered only in terms of floating life or use rate in case of batteries. Probabilities of component failures, to occur before replacement, are not considered.

All other criteria differ in relation to the desired battery system and need therefor be selected individually; even so the process follows the same scheme.

5.3 SIMULATION PROJECT 1

The first Project represents residential off-grid PV-battery systems on the example of a small-scale consumer with a monthly consumption of 80 kWh, being located in the Pantanal region with difficult access, only in combination of road and boat, and far from the next distribution grid. The distribution companies are obliged to increase rural electrification quotes and battery systems can be one possible solution for this application, see regulations ANEEL (2012a, 2012b). The solar powered battery system needs to guaranty 24/7 electricity supply, within the qualitative regulations of named ANEEL regulations. Reference electrification is realized by diesel generators, what is used for economic benchmarking of the PV-battery system as an alternative. The potential customers do not yet have electricity access at the moment or operate own diesel generators if economical achievable. The load curves are built based on the main electricity consumption units for private houses. This includes freezer, air conditioner, electric shower, lightning, TV, electric motors and others. The utilized demand curve is presented in FIGURE 86.

FIGURE 86: PROJECT 1 CONSUMER ELECTRICITY DEMAND CURVE

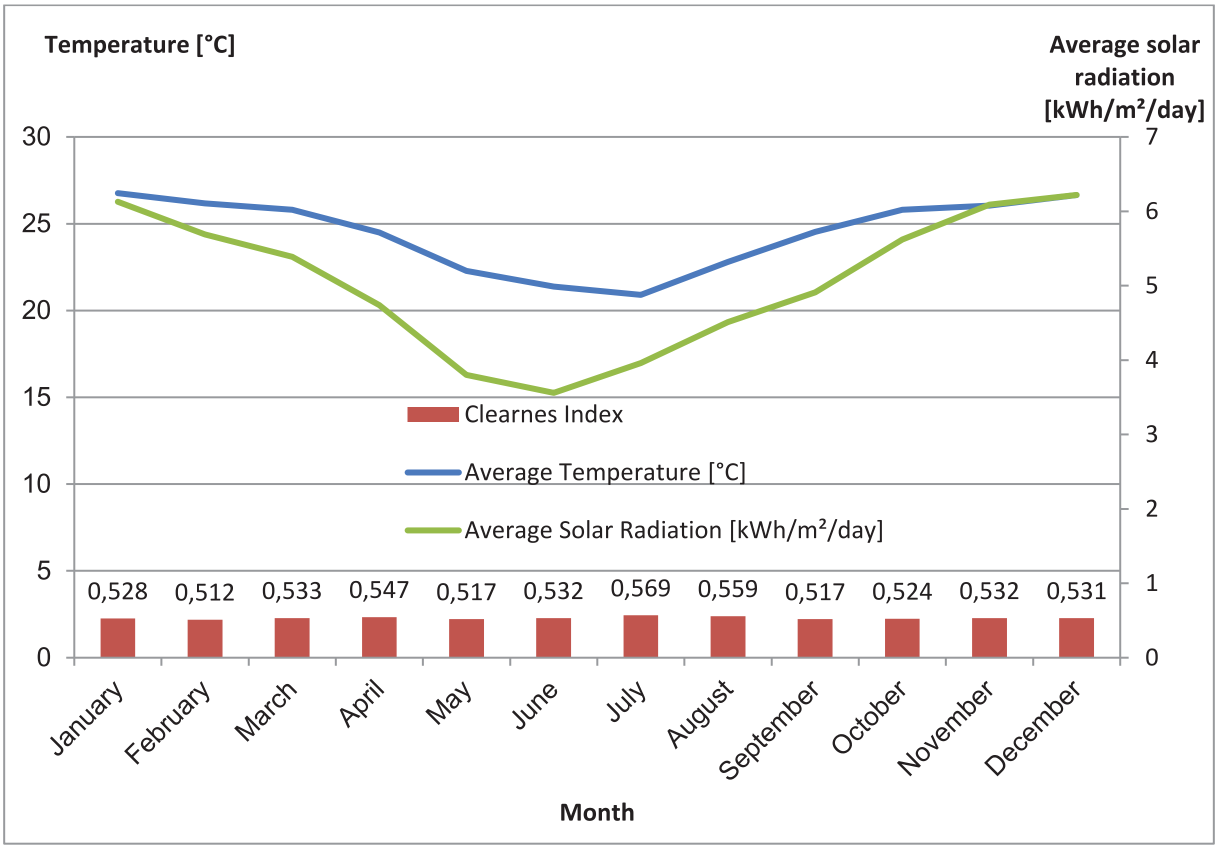


SOURCE: The author

The average daily consumption is 2.6 kWh, with a peak demand of 0.44 kW, the demand curve is considered to be static during the simulations, what has to be considered for system optimizations. Since project 1 is analysing off-grid systems, there is no pre-defined electricity tariff available. In harmony with the cited regulations, the distributer acts as owner and operator of the isolated renewable generation electrification system and the consumer pays a capacity based price for the supplied electricity. The distributer revenue is this way a combination of electricity fees as an income and prevention of penalties as cost saving measure.

The project environment shows no limitations for battery installation but is characterised by hot, dry seasons as well as an extensive raining season over the year. To consider the impact of both, temperature and solar radiation changes, local data must be utilized for system simulations. Solar radiation and temperature data are directly imported, for the selected location of Cuiaba, by the simulation program, from the NASA Surface meteorology and Solar Energy as a monthly average between 1983 and 2005, see FIGURE 87.

FIGURE 87: PROJECT 1 - TEMPERATURE AND SOLAR RADIATION CURVE



SOURCE: NASA (2017)

In line with the normative n °493 from ANEEL, ANEEL (2012a), minimum system autonomy of 48 hours and a minimal power of 1.25 kW have to be guaranteed. Due to the abroad location, difficult access for installation and maintenance must be considered for cost calculations. This is valid for both, the battery system as well as the comparative calculation for diesel generation. The additional costs for transport of equipment and travelling of staff from an initial set point until the project location is considered in a separate scenario, to identify the impact of system location on overall cost and optimization criteria. Therefore, a factor is calculated in relation to the distances in km and the way of travelling, what can be via road, air or water. In this study a medium value of all transportation modes and a distance of 200 km is used, which results in transportation costs of 1,500 R$/trip. These costs are then considered yearly for O&M proposed, as well as for initial system integration. For installation an additional cost of 30 % of the Hardware costs are used, including all Labour and minor material costs like cables. This value is added on all component capital costs but not for replacement. The cost for O&M are added separately to the simulation program under Project, Economics and System Fixed O&M costs. Based on results from Institutos Lactec (2016) the costs for O&M for the PV-battery system, as a total, are considered with a fixed, yearly cost of 1,200 R$, transportation costs not included.

The selection of analysed hardware components is based on the outcome of the roadmap for distributed battery utilization in Brazil and the specific products are selected based on local availability, price and quality expectations. Both battery types are popular for stationary, off-grid applications in combination with PV systems and suitable to climate conditions. The selected PV modules are small sized and therefore favourable for complex transportation conditions. Datasheets for all system components are available online and prices considered for calculations are based on proposals from manufacturer and resellers from 2016, considering an exchange rate of 1 US$: 3.45 Brazilian R$ and an additional cost factor of 2 for all import taxes.

The utilized data and program settings for all simulations are the following. Solar radiation and temperature data are directly imported, for the selected location of Cuiaba, by the simulation program, from the NASA Surface meteorology and Solar Energy as a monthly average between 1983 and 2005, available under NASA (2017).

The compared battery types are a lead carbon battery (12REXC70) from the Chinese manufacturer Narada and an advanced lead acid OPzS type battery (Clean max MFV250) from the national manufacturer Moura. All input data for storage library are summarized in TABLE 32 and TABLE 33.

TABLE 32: PROJECT 1 BATTERY SYSTEM DATA

Battery system data	**Battery 1**	**Battery 2**
General		
Manufacturer	Moura	Narada
type	OPzS similar	Lead Carbon
Name	MFV250	12REXC70
Capacity	250 Ah@C10	70 Ah@C20
Max. Charge Rate [A/Ah]	n.c.	n.c.
Max. Charge Current / (max. const. Charge Current [A])	22	18 / (12)
Max. Discharge Current [A]	30	80
Other round-trip losses [%]	15	20
Functional Model		
Maximum Capacity [Ah] (calculated)	400	65
Nominal Voltage [V]	2	12
Temperature vs. capacity [%]		
Capacity at 15 °C	95	95
Capacity at 25 °C	100	100
Capacity at 35 °C	105	103
Cycle lifetime (cycles to failure for DoD [%])		
DoD 20 [%]	4,400	6,000
DoD 40 [%]	2,900	3,500
DoD 60 [%]	1,900	2,200
Degradation limit for model fitting [%]	20	20
Temperature vs. lifetime (years at temp.)		
lifetime [years] at 25 °C	7	20
lifetime [years] at 35 °C	3.5	10
lifetime [years] at 45 °C	1.7	5
Degradation limit for model fitting [%]	20	20
Thermal		
Max. operating temp. [°C]	45	50
Min. operating [°C]	-10	-20
Lumped thermal model		
Conductance to ambient [W/K]	n.c.	n.c.
Specific heat capacity [J/kg*K]	n.c.	n.c.

SOURCE: The author

TABLE 33: PROJECT 1 BATTERY SYSTEM DATA, CONTINUATION

Battery system data	Battery 1	Battery 2
Defaults		
Quantity	1	1
Capital [$] ((battery module + housing structure) *1.3)	800	1,365
Replacement [$] (battery only)	550	850
O&M [$/year]	0	0
Search Space		
case 1 (consumption 80kWh/month)	24	8
case 2 (consumption 300kWh/month)	96	32
Site Specific Input		
String Size	24	4
Initial state of Charge [%]	100	100
Minimum State of Charge [%]	30	30
Capacity degradation limit [%]	20	20
Maintenance Schedule	n.c.	n.c.

SOURCE: The author

Some of the required information is not or not direct delivered by the manufacturer; in this case the values are transformed in the right form by calculations or selected in respect to literature, see chapter 2. The maximal charge and discharge rate are limited by both, the battery characteristics and the converter, which is controlling the energy flow between battery and consumer.

The selected PV system is based on multicrystalline modules with a maximal power output of 150 W (YL150P-17b) from the manufacturer Yingli Solar. The modules are smaller in size what is an advantage for transportation to rural system locations and handling. The datasheet is available to download at Yingli Solar (2017) and the used simulation input data is summarized in TABLE 34.

TABLE 34: TABLE 34: PROJECT 1 PV SYSTEM DATA

PV	PV 1
General	
Manufacturer	Yingli
Type	Multicrystalline
Name	YL150P-17B
Electrical Bus (AC/DC)	DC
Lifetime [years]	25
Derating Factor [%]	80
Converter	
Ignore dedicated converter	ok
Temperature	
Consider temperature effects	ok
Temperature effects on power [%/°C]	-0,45
Nominal operating cell temperature [°C]	46
Efficiency at standard test conditions [%]	15
Defaults	
Cost table set “P_{max} per module in kW”	0.15
Capital [$] ((PV module + mounting structure) *1.3)	1,200
Replacement [$]	550
O&M [$]	n.c.
Search Space	
Available capacities in kWp	0.15 – 1.5
Ground Reflectance [%]	20
Tracking System	No
Use default slope	Ok
Use default azimuth	Ok

SOURCE: The author

The last hardware component to be imported to the library is the converter. The converter includes the function of the charge controller (CC) and the inverter (INV). The charge controller is working on the DC side of the system, controlling the optimal voltage level to charge and operate the batteries and protecting them from critical voltage level, beyond safe system borders. The inverter is the interface between DC operation of the PV-battery system and the AC face of consumer network and consumption. For the charge control, the model “PL20” from Plasmatronics is chosen, datasheet available under Plasmatronics (2017), whereby the selected “Media: 1.5kVA” inverter is produced by the company CE+T, see CE+T (2017). Due to modulation system restrictions of Homer Energy, which does not enable the implantation of two separate converter components, a combination of both is added to the library as a single component, as shown in Table 35.

TABLE 35: PROJECT 1 CONVERTER DATA

Converter	Charge controller (CC)	Inverter (INV)	Representative CC+INV component
General			
Name	Plasmatronics PL20	Media: 1.5kVA	CC+INV Project1
Manufacturer	Plasmatronics	CE+T	Plasmatronics & CE+T
Defaults			
Capacity in kW			1.5
Capital [$]	1,000	7,000	11,700 ((7,000+2*1,000)*1,3)
Replacement [$]	1,000	7,000	2,000 (2*1,000 for CC)
O&M [$]	n.c.	n.c.	n.c.
Search Space – Size [kW]			
case 1 (consumption 80kWh/month)	1.152 (2*48V*20A)	1.5	1.5
Inverter Input			
Lifetime [years]	7	20	20
Efficiency [%]	n.c.	90	90
Rectifier Input			
Relative Capacity	0	0	0
Efficiency [%]	0	0	0

SOURCE: The author

To compare the PV-battery system with conventional solutions, a generator, from the manufacturer Nagano, see Nagano (2017), is taken. Since datasheets do not inform about principal criteria in terms of lifetime and efficiency, the default settings from Homer Energy are only adjusted to the generators nominal capacity, see Table 36.

TABLE 36: PROJECT 1 DIESEL GENERATOR DATA

Generator	1
Copy “Generator”	
Name	Generator Project 1
Manufacturer	Nagano
Product Name	ND3200M
Minimum Load Ratio [%]	25
Lifetime [Hours]	15,000
Fuel	
Reference generator capacity [kVA]	3.5
Defaults	
Cost [kW]	3.5
Capital (4,000 *1,3) [$]	4,550
Replacement [$]	3,500

SOURCE: The author

The fuel costs for the diesel generator must be added, to allow a comparative operation cost calculation between the PV-battery system and a conventional diesel generator. Relevant input data for project 1 is the fuel cost only, see Table 37.

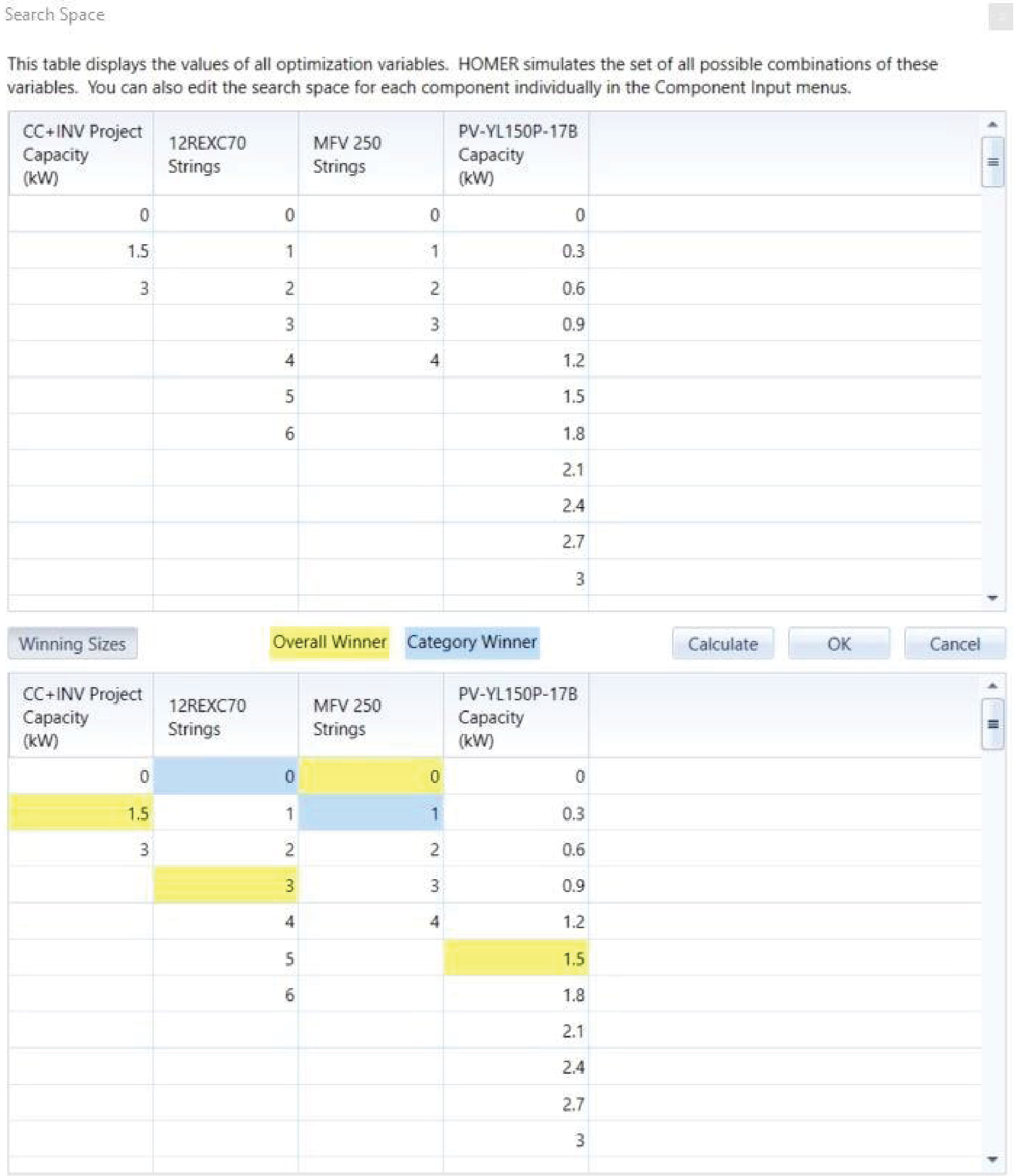
TABLE 37: PROJECT 1 FUEL COST DATA

Fuel	1
Copy “Diesel”	
Name	Diesel Project 1
Fuel Type	Conventional
Limits and Prices	
Diesel Fuel Price [$/L]	3.5
Limit Consumption (L)	No

SOURCE: The author

After preparing of all relevant input data, the costs and energetic performance of the different system constellations is simulated. All selected variations on component utilization, optional utilization is symbolised by a zero, and quantity are printed in the Search Space, see FIGURE 88.

FIGURE 88: PROJECT 1 SEARCH SPACE OF ANALYSED SYSTEM CONSTELLATIONS



This table displays the values of all optimization variables. HOMER simulates the set of all possible combinations of these variables. You can also edit the search space for each component individually in the Component Input menus.

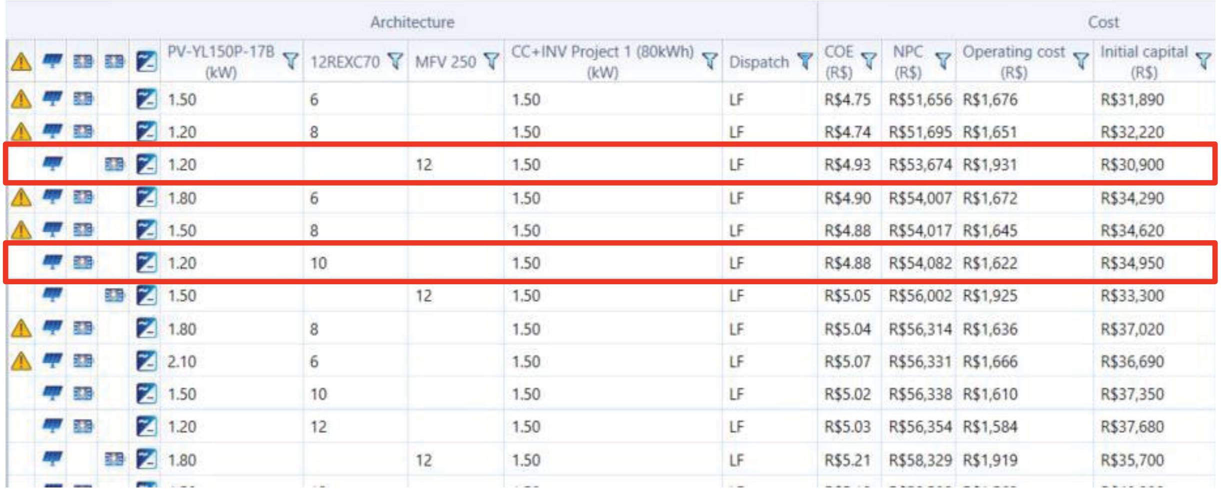
CC+INV Project Capacity (kW)	12REXC70 Strings	MFV 250 Strings	PV-YL150P-17B Capacity (kW)
0	0	0	0
1.5	1	1	0.3
3	2	2	0.6
	3	3	0.9
	4	4	1.2
	5		1.5
	6		1.8
			2.1
			2.4
			2.7
			3

CC+INV Project Capacity (kW)	12REXC70 Strings	MFV 250 Strings	PV-YL150P-17B Capacity (kW)
0	0	0	0
1.5	1	1	0.3
3	2	2	0.6
	3	3	0.9
	4	4	1.2
	5		1.5
	6		1.8
			2.1
			2.4
			2.7
			3

SOURCE: The author, screen shot from Homer Energy

The overall winner in terms of lowest average cost per useful energy (COE), produced by the system [$/kWh], is already indicated as a combination of 1.5 kWp PV + six batteries of the type 12REXC70 and one 1.5 kW converter with two 20 A charge controllers, presenting a COE of 4.75 Real per consumed kWh of electricity, compare FIGURE 89. Anyway, this solution is not suitable under given requirements, since the limitation of battery autonomy do not fulfil the 48 hours target. Considering the optimization cases, the cheapest viable system, with a COE of 4.88 $/kWh, can be identified, being a combination of 1.2 kWp PV, with 10 units of the 12REXC70 battery and one 1.5 kW converter with two 20 A charge controllers.

FIGURE 89: PROJECT 1 OPTIMIZATION CASES OVERVIEW WITHOUT TRANSPORTATION COSTS

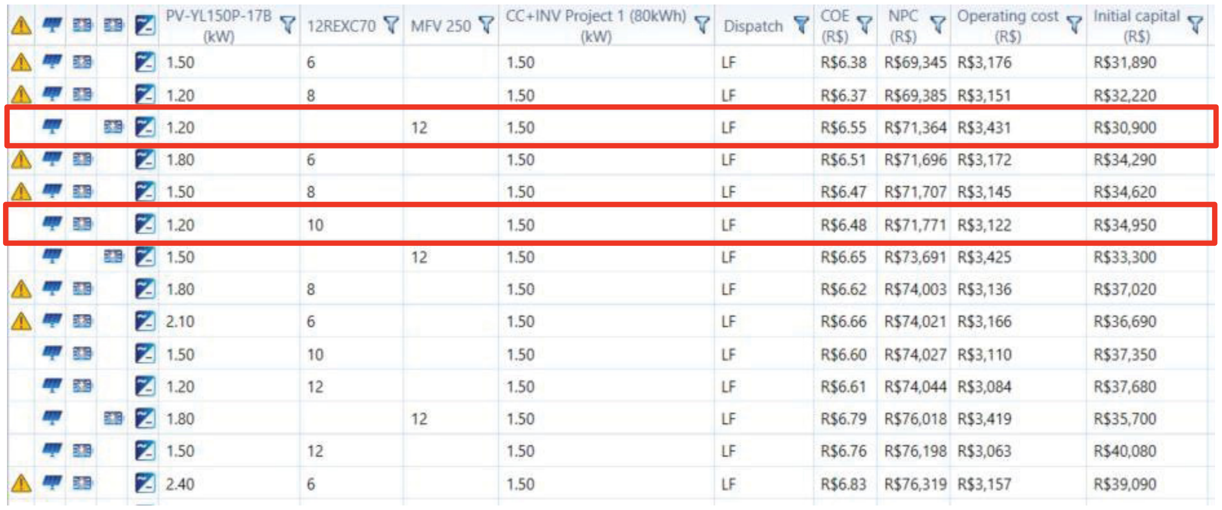


Architecture						Cost			
⚠	PV-YL150P-17B (kW)	12REXC70	MFV 250	CC+INV Project 1 (80kWh) (kW)	Dispatch	COE (R$)	NPC (R$)	Operating cost (R$)	Initial capital (R$)
⚠	1.50	6		1.50	LF	R$4.75	R$51,656	R$1,676	R$31,890
⚠	1.20	8		1.50	LF	R$4.74	R$51,695	R$1,651	R$32,220
	1.20		12	1.50	LF	R$4.93	R$53,674	R$1,931	R$30,900
⚠	1.80	6		1.50	LF	R$4.90	R$54,007	R$1,672	R$34,290
⚠	1.50	8		1.50	LF	R$4.88	R$54,017	R$1,645	R$34,620
	1.20	10		1.50	LF	R$4.88	R$54,082	R$1,622	R$34,950
	1.50		12	1.50	LF	R$5.05	R$56,002	R$1,925	R$33,300
⚠	1.80	8		1.50	LF	R$5.04	R$56,314	R$1,636	R$37,020
⚠	2.10	6		1.50	LF	R$5.07	R$56,331	R$1,666	R$36,690
	1.50	10		1.50	LF	R$5.02	R$56,338	R$1,610	R$37,350
	1.20	12		1.50	LF	R$5.03	R$56,354	R$1,584	R$37,680
	1.80		12	1.50	LF	R$5.21	R$58,329	R$1,919	R$35,700

SOURCE: The author, screen shot from Homer Energy

The alternative battery, as a combination of 1.2 kWp PV, with 12 units of the MFV250 battery and one 1.5 kW converter with two 20 A charge controllers, is the second cheapest solution, within application restrictions, showing COE five cents higher than the cheapest. Taking into consideration the transportation costs, which were considered optionally, to see the impact of project locations with difficult access characteristics, the COE of the same systems rise to 6.48 $/kWh for the cheapest Narada based and 6.55 $/kWh for the best Moura based battery system, compare FIGURE 90.

FIGURE 90: PROJECT 1 OPTIMIZATION CASES OVERVIEW WITH TRANSPORTATION COSTS



⚠	PV-YL150P-17B (kW)	12REXC70	MFV 250	CC+INV Project 1 (80kWh) (kW)	Dispatch	COE (R$)	NPC (R$)	Operating cost (R$)	Initial capital (R$)
⚠	1.50	6		1.50	LF	R$6.38	R$69,345	R$3,176	R$31,890
⚠	1.20	8		1.50	LF	R$6.37	R$69,385	R$3,151	R$32,220
	1.20		12	1.50	LF	R$6.55	R$71,364	R$3,431	R$30,900
⚠	1.80	6		1.50	LF	R$6.51	R$71,696	R$3,172	R$34,290
⚠	1.50	8		1.50	LF	R$6.47	R$71,707	R$3,145	R$34,620
	1.20	10		1.50	LF	R$6.48	R$71,771	R$3,122	R$34,950
	1.50		12	1.50	LF	R$6.65	R$73,691	R$3,425	R$33,300
⚠	1.80	8		1.50	LF	R$6.62	R$74,003	R$3,136	R$37,020
⚠	2.10	6		1.50	LF	R$6.66	R$74,021	R$3,166	R$36,690
	1.50	10		1.50	LF	R$6.60	R$74,027	R$3,110	R$37,350
	1.20	12		1.50	LF	R$6.61	R$74,044	R$3,084	R$37,680
	1.80		12	1.50	LF	R$6.79	R$76,018	R$3,419	R$35,700
	1.50	12		1.50	LF	R$6.76	R$76,198	R$3,063	R$40,080
⚠	2.40	6		1.50	LF	R$6.83	R$76,319	R$3,157	R$39,090

SOURCE: The author, screen shot from Homer Energy

Since the transportation cost are considered statically for each year of operation, as a part of the generalized O&M costs, further analysis is limited to the cheapest system, without transportation costs. The simulation results can be analysed in relation to cost, energetic balance, renewable generation and performance values of all system components.

The Cost summary is given in form of net present or annualized values for each system component, as shown in Table 38.

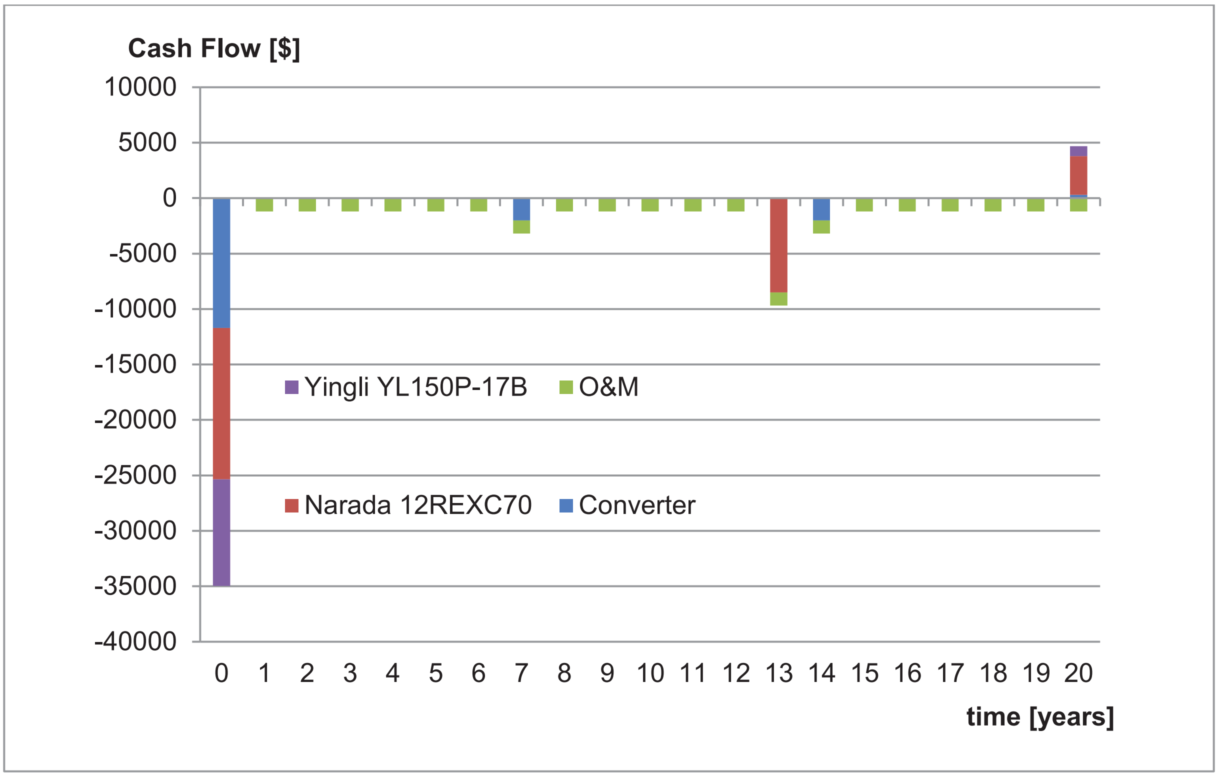
TABLE 38: PROJECT 1 NET PRESENT COST OVERVIEW

Component	Capital [$]	Replacement [$]	O&M [$]	Salvage [$]	Total [$]
Converter	R$11,700	R$2,285	R$0	(R$95)	R$13,890
12REXC70	R$13,650	R$4,248	R$0	(R$1,166)	R$16,732
O&M	R$0	R$0	R$14,151	R$0	R$14,151
YL150P-17B	R$9,600	R$0	R$0	(R$293)	R$9,307
System	R$34,950	R$6,533	R$14,151	(R$1,554)	R$54,080

SOURCE: The author

The nominal cash flow over the whole project time can be split by cost type, or by component, as illustrated in FIGURE 91.

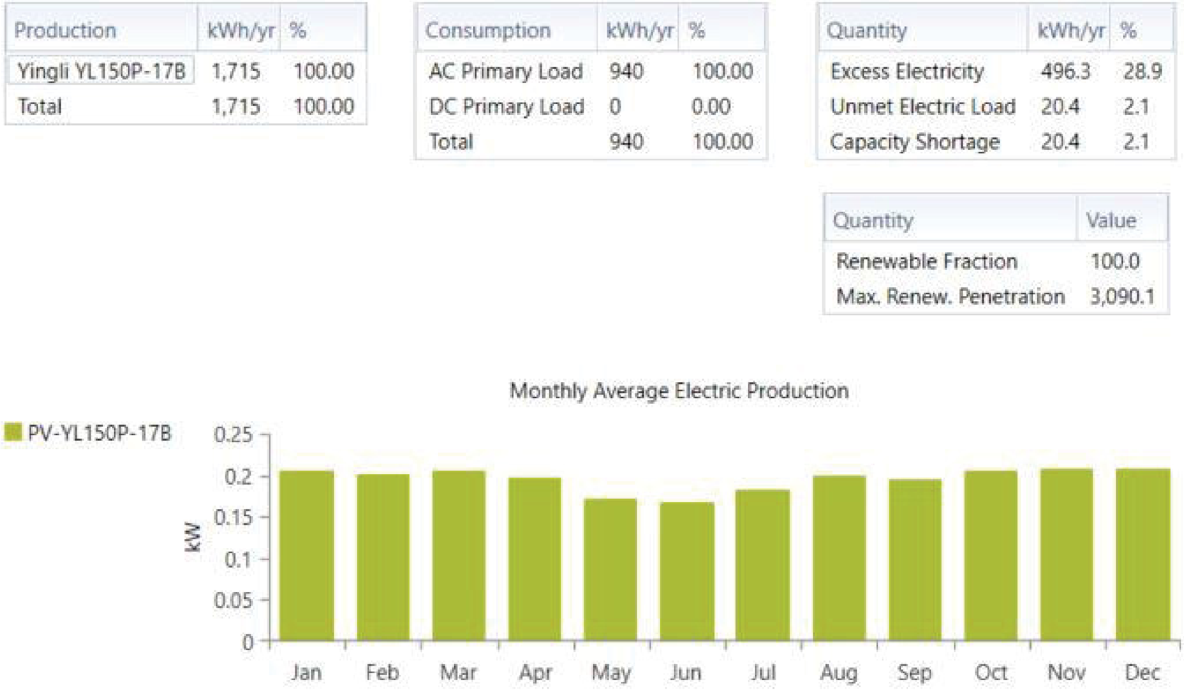
FIGURE 91: PROJECT 1 NOMINAL CASH FLOW



SOURCE: The author

Year Zero represents the year of system implementation, when the major investment must be done. The positive value in the last year stands for the residual system value in relation to remaining expected lifetime. In terms of electricity balance, an overview of production and consumption rates is provided, important information about excess production and unmet demand rates. As shown in FIGURE 92, a capacity shortage of 2.1 % can be realized by the system under assumed conditions.

FIGURE 92: PROJECT 1 ELECTRICAL ENERGY RESULTS



Production	kWh/yr	%
Yingli YL150P-17B	1,715	100.00
Total	1,715	100.00

Consumption	kWh/yr	%
AC Primary Load	940	100.00
DC Primary Load	0	0.00
Total	940	100.00

Quantity	kWh/yr	%
Excess Electricity	496.3	28.9
Unmet Electric Load	20.4	2.1
Capacity Shortage	20.4	2.1

Quantity	Value
Renewable Fraction	100.0
Max. Renew. Penetration	3,090.1

SOURCE: The author

The monthly average electricity production indicates seasonal fluctuations, which explain the high rate of 28.9 % of PV overproduction. The share of renewable electricity production can be analysed separately and compared to alternative sources, such as grid or diesel generators. In case of project 1, where all production is based on solar energy this comparison is not required. Nevertheless, it is notable that the total PV production represents over 180 % of the demand and peak output reaches a power level over two times higher than the maximum demand.

A general overview about battery system dimensioning and operation criteria is provided, to enable control of results in relation to framework conditions, such as autonomy or bus voltage levels and results of best practice for lifetime vs. investment cost relations. The results of project 1 are summed up in TABLE 39.

TABLE 39: PROJECT 1 GENERAL BATTERY SYSTEM RESULTS

Battery	**Value**	**Unit**
Batteries	10	
String Size	2	
Strings in Parallel	5	
Bus Voltage	24	
Autonomy	57.3	hr
Storage Wear Cost	0	R$/kWh
Nominal Capacity	7.85	kWh
Usable Nominal Capacity	4.71	kWh
Lifetime Throughput	9,679.90	kWh
Expected Life	12.6	yr
Average Energy Cost	0	R$/kWh
Energy In	859.57	kWh/yr
Energy Out	685.17	kWh/yr
Storage Depletion	2.09	kWh/yr
Losses	172.31	kWh/yr
Annual Throughput	768.34	kWh/yr

SOURCE: The author

The PV system can be analysed in terms of production, utilization rate and economic performance as an individual component. The general performance results of the PV system in project 1 are shown in Table 40.

TABLE 40: PROJECT 1 GENERAL PV PERFORMANCE RESULTS

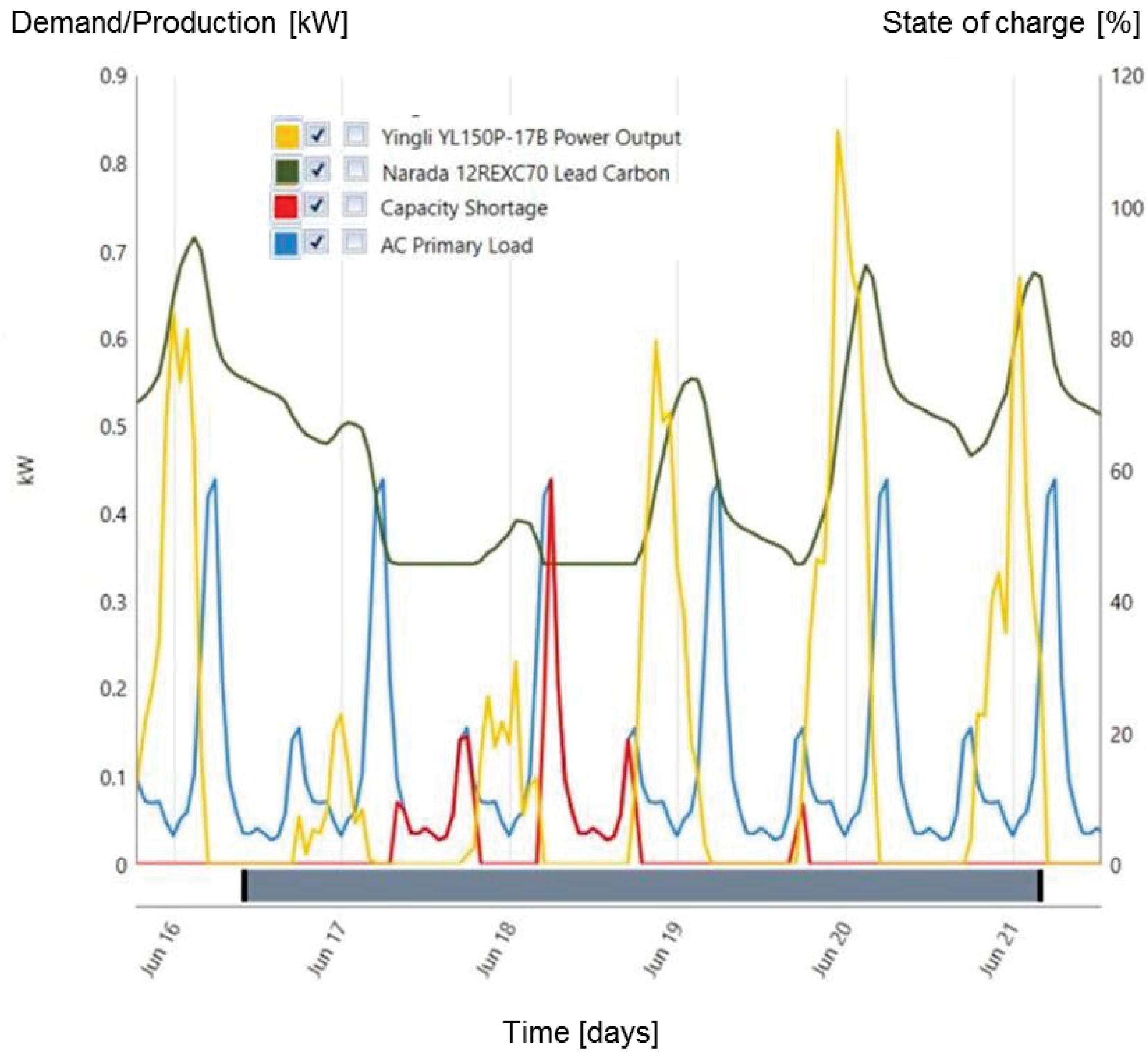
Quantity	Value	Units
Rated Capacity	1.2	kW
Mean Output	0.2	kW
Mean Output	4.7	kWh/d
Capacity Factor	16.31	%
Total Production	1,714.60	kWh/yr
Minimum Output	0	kW
Maximum Output	1.01	kW
PV Penetration	179	%
Hours of Operation	4,401	hrs/yr
Levelized Cost	0.46	R$/kWh

SOURCE: The author

The performance results of the converter are delivered in terms of capacity, utilization rate, operation time and energy losses. The capacity factors can be analysed to optimize the search space, to identify the possibility of using different dimensions. In case of Project 1 the dimension is appropriate, in relation to the PV power.

The plot option allows detailed, graphical analysis and comparison of a great variability of technical relevant system operation characteristics. So, it offers the possibility to understand, how different system parameters interact, what can help the optimization process for better electrification solutions. FIGURE 93 shows, how two days with low solar radiation force the battery to discharge until the minimum state of charge, followed by capacity shortage, which can only on the third day of full sunshine be totally recovered.

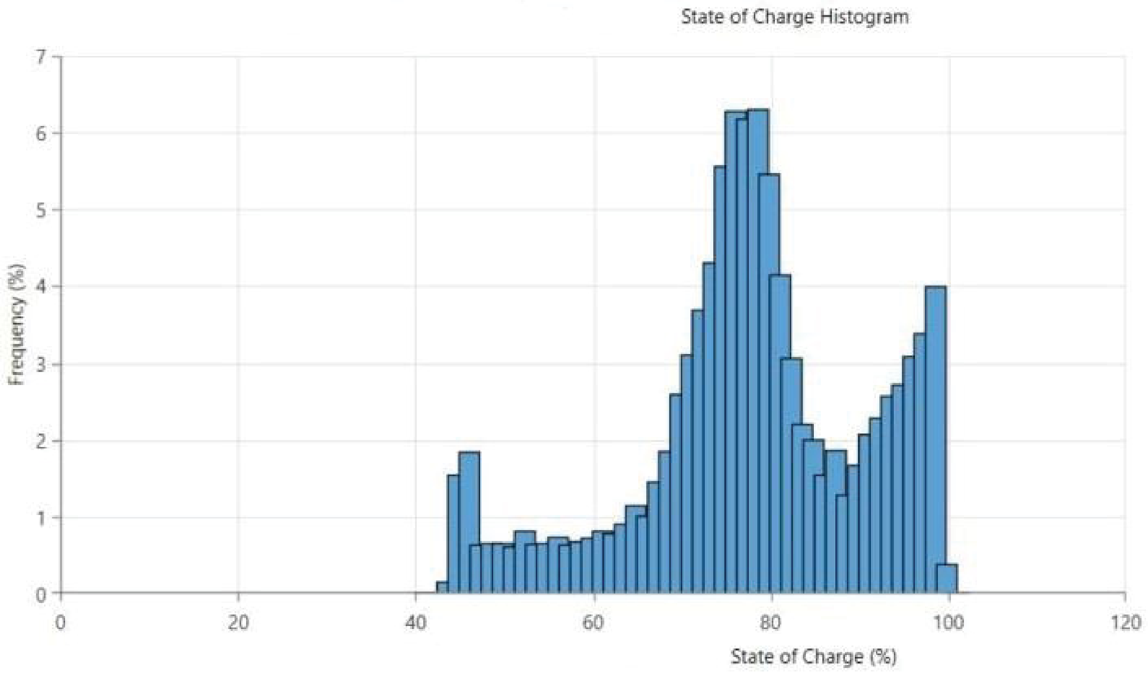
FIGURE 93: PROJECT 1 GRAPHICAL ANALYSIS OF SYSTEM PERFORMANCE - CAPACITY SHORTAGE EVENT



SOURCE: The author

Another interesting observation to be done is the control of state of charge of the battery. Most battery types are sensitive to discharge depth in terms of lifetime and the framework condition of 48 hours autonomy do also require sufficient back up capacity, to serve the full load over this period in extreme situations, without additional electricity supply from other generation sources. FIGURE 94 shows the frequency, in which the battery reaches certain state of charge during analysed operation conditions. Based on this information the selection of an alternative system composition might be the more convenient solution.

FIGURE 94: PROJECT 1 - BATTERY STATE OF CHARGE DISTRIBUTION



SOURCE: The author

To evaluate the viability of PV-battery systems in rural off-grid applications, the costs for diesel generation as a conventional alternative are calculated. Under consideration of the input data, presented in Table 36 and Table 37, the net present cost characteristics can be observed in Table 41.

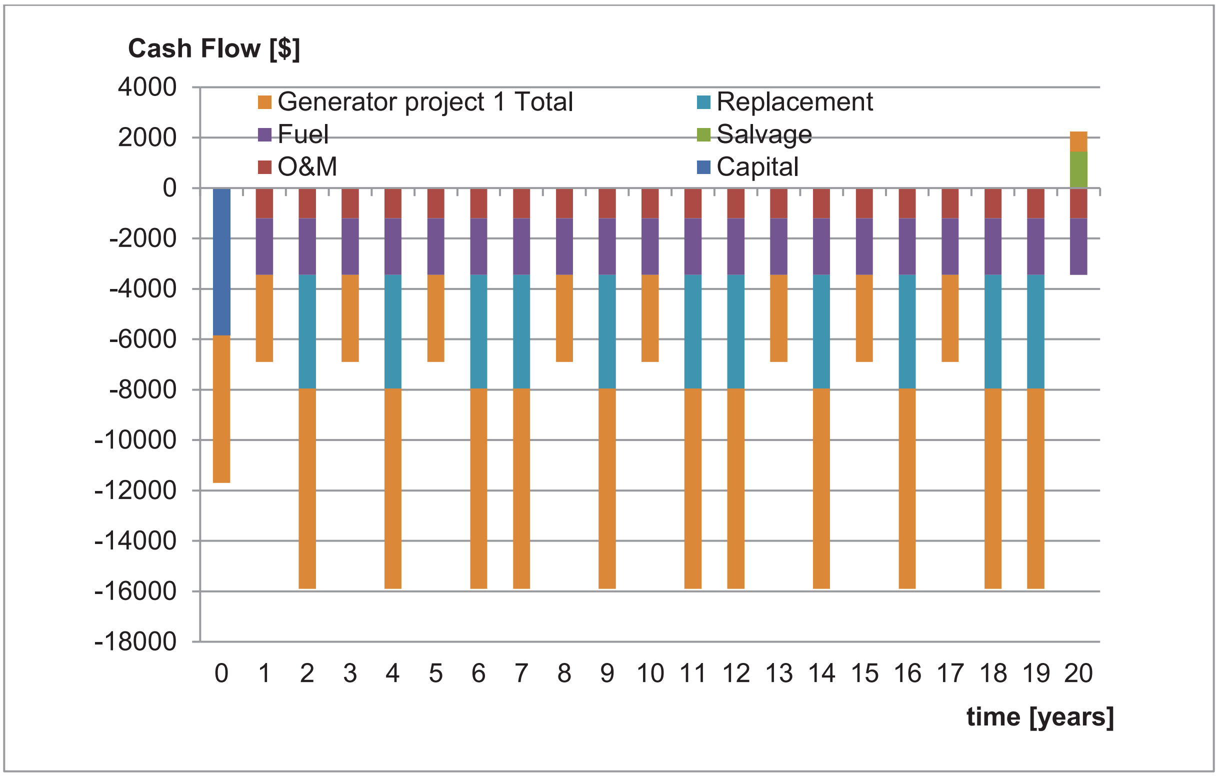
TABLE 41: PROJECT 1 DIESEL GENERATION COST OVERVIEW

Component	Capital [$]	O&M [$]	Replacement [$]	Fuel [$]	Salvage	Total [$]
Generator	R$5,850	R$29,381	R$0	R$26,506	(R$479)	R$61,258
O&M	R$0	R$0	R$14,151	R$0	R$0	R$14,151
System	R$5,850	R$29,381	R$14,151	R$26,506	(R$479)	R$75,409

SOURCE: The author

Due to the high frequency of replacement and under consideration of the same cost for O&M, as used for the PV-battery system, a COE of 6.66 $/kWh occurs. The nominal cash flow of the diesel generator is presented in FIGURE 95, what visualises the main characteristic difference between renewable and fossil based generation units. In contrast to the PV-battery system with an initial high investment, but only long-term replacements or even components with lifetimes superior to the project horizon, the diesel generation system is characterised by comparative low initial investment coupled with high running costs for fuel and frequent reinvestments because of low lifetime expectancies.

FIGURE 95: PROJECT 1 NOMINAL CASH FLOW OF DIESEL GENERATION



SOURCE: The author

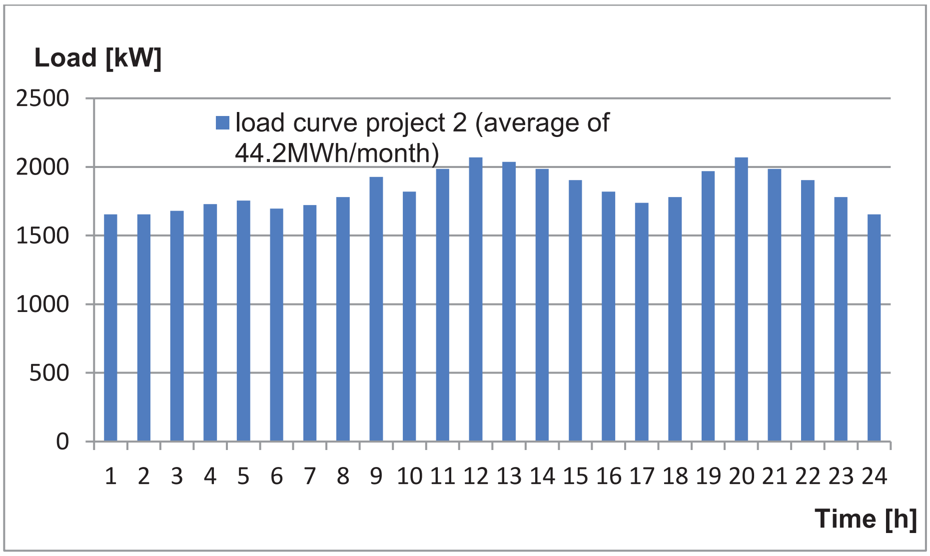
This value might not be very representative, because of an over dimensioned system, resulting in low efficiency rates and low lifetime because of an uninterrupted operation. The simplified assumption of the same costs for O$M as applied for the PV-battery system are also a point of discussion, looking at two systems of totally different nature. On the other side a combustion engine requires way more attention for refuelling, oil change and major maintenances.

5.4 SIMULATION PROJECT 2

Isolated systems, powered by diesel generators suffer from high electricity generation costs due to elevated diesel prices and low efficiencies operation schemes. PV system integration can support diesel consumption reduction but due to fluctuating generations, effective shut down of diesel generation units are not possible under system safety and flexibility requirements. The integration of medium to large scale battery storage systems are expected to support PV integration, temporarily diesel generator shut down, overall fuel reduction and electricity cost and quality improvement.

Project 2 simulates the utilization of a 1,510 kWh li-ion battery system as part of an isolated micro grid, operated in MV level and supplying about 934 consumer units. The battery is expected to improve the energy quality under combined PV and diesel generation. The installed generation capacity consists of four diesel generators with a combined power of 4,978 kW plus 1,120 kW from a fifth backup generator and 950 kWp from two PV plants. Due to generation flexibility regulations the PV generation is currently limited to 675 kW, to keep the generators run in the range of 60 % to 80 % of the nominal capacity. The distribution grid operator is owner and operator of the battery system. The average daily consumption is about 44 MWh/day with a peak demand of 2.6 MW. FIGURE 96 shows the baseline demand, which is simulated under application of a 5 % day-to-day and time step random variability.

FIGURE 96: PROJECT 2 DEMAND CURVE



SOURCE: The author

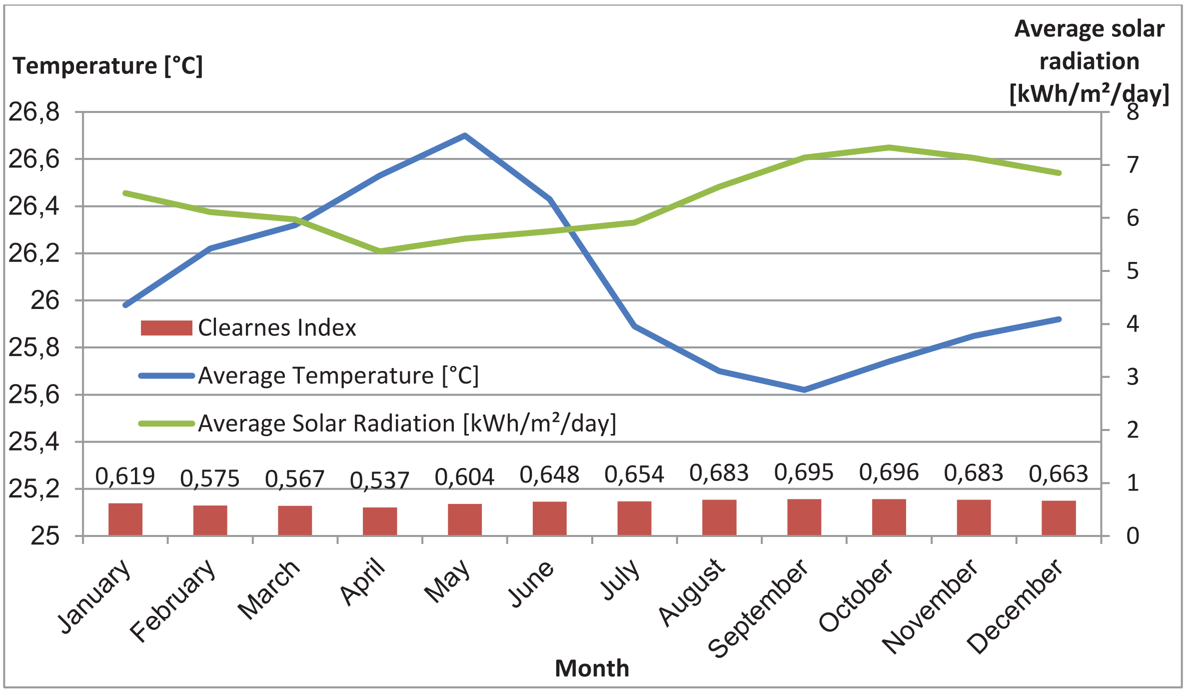
The distribution grid operator is owner, operator and consumer of the battery system, which is used as an internal component of the generation utility. The battery value is expected in form of reduced diesel consumption, increased PV generation and overall cost minimization.

The project is located on the island Fernando de Noronha, which belongs to the state Pernambuco and is in a distance about 350 km from the continent. The island is under various environmental protection programs, which include:

- In parts defined as an ambient protection area (APA - *Área de Proteção Ambiental Fernando de Noronha - Rocas - São Pedro e São Paulo*) and national park, which is under controll of the Institute for Biodiversity (*ICMBio - Instituto Chico Mendes de Conservação da Biodiversidade*)
- The area is considered as part of the national marine park (*Parque Nacional Marinho*)
- Biosphere Reserve of the Atlantic Forest (*Reserva da Biosfera da Mata Atlântica*) and World Heritage Site, as acknowledged by the UNO via UNESCO program.

The climatic data of the project location, used for simulations, are shown in FIGURE 97.

FIGURE 97: PROJECT 2 CLIMATE DATA



SOURCE: NASA (2017)

The consumers are supplied with electricity over a medium and low voltage micro grid, which is not a limiting factor for consumer supply or the desired battery installation. Until today the off-grid diesel generation is subsidised by the Energy Development Account (*CDE - Conta de Desenvolvimento Energético*), which is a sectoral charge that has several objectives. One of them is to support the generation of electric energy in isolated systems with the so-called bill of fuel cost (*Conta de Consumo de Combustíveis – CCC*).

The operation of a 1,500 kWh battery system is analysed in terms of diesel consumption and cost minimization. Diesel and PV generators are considered as existing and operating components and costs are only considered in terms of O&M and eventual reinvestments. Electricity tariffs are not considered for this application, but might become relevant after white tariff implementation.

To ensure sufficient primary regulation capacity, the diesel generators are operated within 60 and 80 % of the nominal capacity. The available overcapacity is used to guaranty supply during maintenance works and as reserve for major disturbances. To consider the operation parameters for the simulations, the respective capacities are downsized to 80 % and a minimum operation capacity of 75 % is applied. Since the simulation program offers no possibility to apply alternating operation between the five generators, only three are considered for the simulations. The fuel consumption is slope is adjusted to the current situation, which shows a yearly consumption of around 4.5 million litres. An overview of all diesel generator data input is given by TABLE 42.

TABLE 42: PROJECT 2 DIESEL GENERATOR SIMULATION DATA

Generator	1	2	3
Copy "Generator"			
Name	P2-00G1	P2-00G2	P2-00G3
Manufacturer	CUMMINS	CUMMINS	CUMMINS
Product Name	KTA50-G9	KTA50-G3	KTA50-G9
Minimum Load Ratio [%]	75	75	75
Lifetime [Hours]	15,000	15,000	15,000
Minimum Runtime [Minutes]	240	240	240
Fuel			
Reference generator active capacity [kW]	1,286	1,120	1,286
Reference generator capacity [kVA]	1,608	1,400	1,608
Fuel Curve			
Slope [L/hr/kW output]	0.2793	0.2793	0.2793
Costs			
Capacity (kW)	1,029	896	1,029
Capital [R$]	0	0	0
Replacement [R$]	500,000	500,000	500,000
O&M [R$/hour]	2	1.5	2
Fuel Resource			
Diesel Fuel Price [R$/L]	4.5	4.5	4.5

SOURCE: The author

The PV system is already existing and simulated under the same conditions as project 1, with the difference of an overall installed system power of 950 kWp and without initial investment costs.

For this project a lithium ion battery system is analysed, which offers deep cycling and high energy density advantages. Different battery types or combinations are possible, whereby advantages require an additional study. Battery overall system cost of R$ 8,778,287.22 inclusive converters and control system are applied. The cost for installations are considered with R$ 1,665,000.00 what corresponds to 19 % of the hardware cost. The simulated battery is a generic Li-ion battery with a capacity of 1,510 kWh, as specified in TABLE 43 and TABLE 44.

TABLE 43: PROJECT 2 BATTERY SIMULATION DATA

Battery system data	**Battery 1**
General	
Manufacturer	Generic
type	Li-ion
Name	P2 Li-ion battery
Capacity [kWh]	1,500
Max. Charge Rate [A/Ah]	n.c.
Max. Charge Current / (max. const. Charge Current [A])	320
Max. Discharge Current [A]	320
Other round-trip losses [%]	7.5
Functional Model	
Maximum Capacity [Ah] (calculated)	40
Nominal Voltage [V]	3.7
Temperature vs. capacity [%]	
Capacity at -20 °C	95
Capacity at 25 °C	100
Capacity at 55 °C	105
Cycle lifetime (cycles to failure for DoD [%])	
DoD 20 [%]	13,000
DoD 50 [%]	6,500
DoD 80 [%]	3,500
DoD 100 [%]	2,000
Degradation limit for model fitting [%]	
Temperature vs. lifetime (years at temp.)	
lifetime [years] at 20 °C	20
lifetime [years] at 35 °C	20
lifetime [years] at 40 °C	14
lifetime [years] at 45 °C	8
lifetime [years] at 50 °C	4
lifetime [years] at 55 °C	2
lifetime [years] at 60 °C	1
Degradation limit for model fitting [%]	20
Thermal	
Max. operating temp. [°C]	60
Min. operating [°C]	-20
Lumped thermal model	
Conductance to ambient [W/K]	n.c.
Specific heat capacity [J/kg*K]	n.c.

SOURCE: The author

TABLE 44: PROJECT 2 BATTERY SIMULATION DATA, CONTINUATION

Battery system data	Battery 1
Defaults	
Quantity	10,150
Capital [$] (battery + housing + converter + installation)	10,443,287
Replacement [$] (battery only)	8,778,287
O&M [$/year]	
Search Space	
Site Specific Input	10,150
String Size	175
Initial state of Charge [%]	20
Minimum State of Charge [%]	20
Capacity degradation limit [%]	20
Maintenance Schedule	n.c.

SOURCE: The author

Further a generic converter, with zero costs, an efficiency of 90 % and a size of 1,100 kW is considered to enable the simulations.

The system is simulated in two steps, once under consideration of the state of the art, without battery application and limited PV generation, and once with the full PV capacity and a 1.510 kWh li-ion battery. The main results in terms of fuel consumption, renewable penetration and costs are compared for both cases in Table 45.

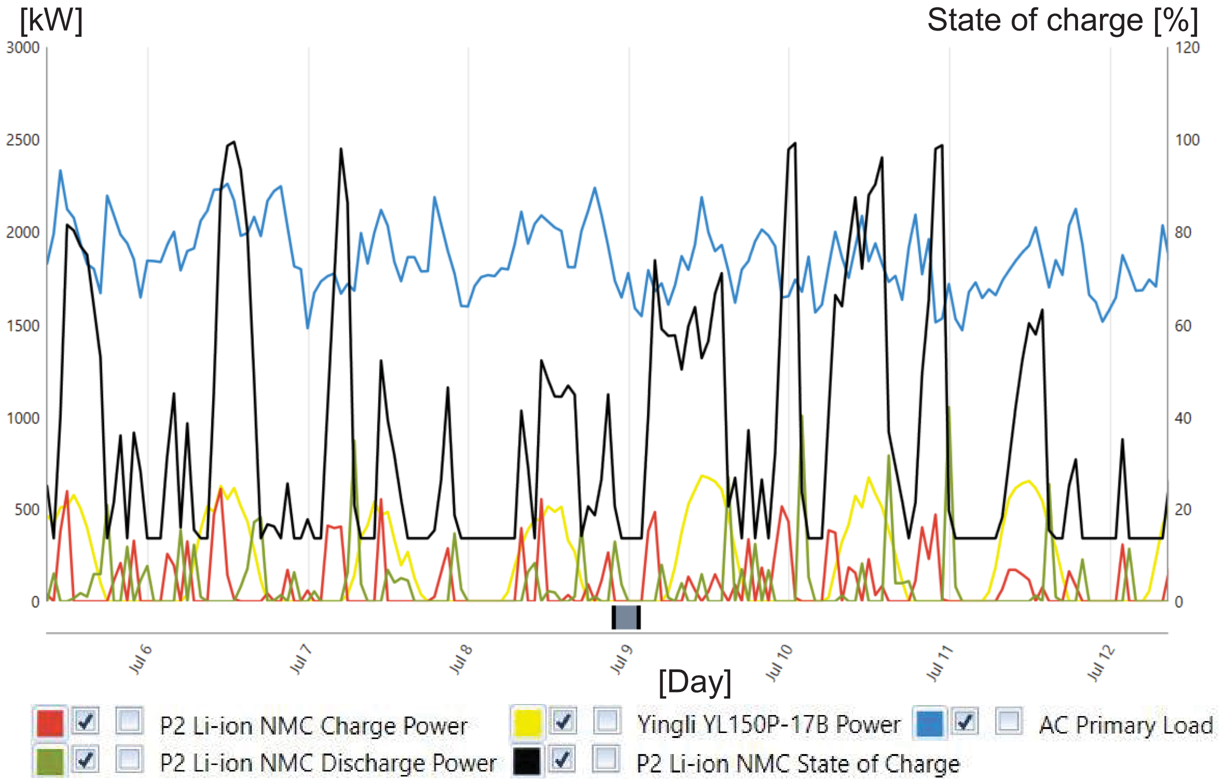
TABLE 45: PROJECT 2 STATUS QUO VS. BATTERY UTILIZATION RESULTS

Generator	Status Quo	With battery system
Diesel generator capacity	2,954	2,954
PV capacity [kWp]	675	950
PV production [kWh/year]	1,156,714	1,627,966
Total share of load served by PV [%]	0.37	8.08
Battery capacity [kWh]	none	1,486
Diesel consumption (Litres per year)	4,541,716	4,190,919
COE [R$/kWh]	1.31	1.33
Fuel savings [%]	none	7.7

SOURCE: The author

Generally, there can be made three major observations, first the effective reduction of fuel consumption of nearly 8 %, second the increasing share of demand supply by renewable generation from less than a half up to over eight percent and third the negative economic effect under assumed battery costs. Since the marginal costs for PV generation are zero, generation is always used, when available. The generators are running in alternating order, within the limitations of maintenance schedules and resting times, as a function of optimized lifetime and costs. Therefore, the battery utilization is used, to capture combined excess generation and allow generator shot down during discharge periods. This way, there is no direct relation between battery cycling and PV generation, but more a dependence on diesel generator restrictions observable. An insight into the battery operation scheme is given for a random seven-day period in FIGURE 98.

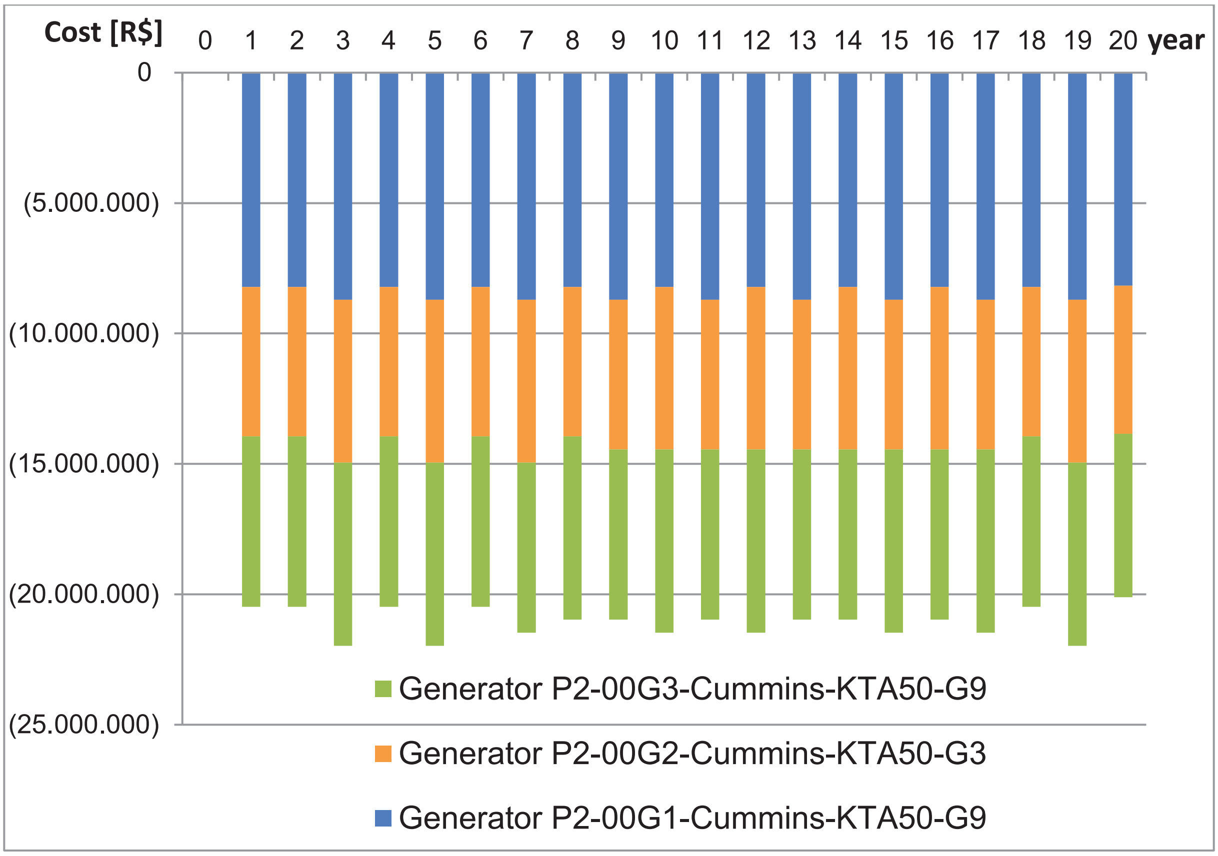
FIGURE 98: PROJECT 3 BATTERY OPERATION SCHEME



SOURCE: The author

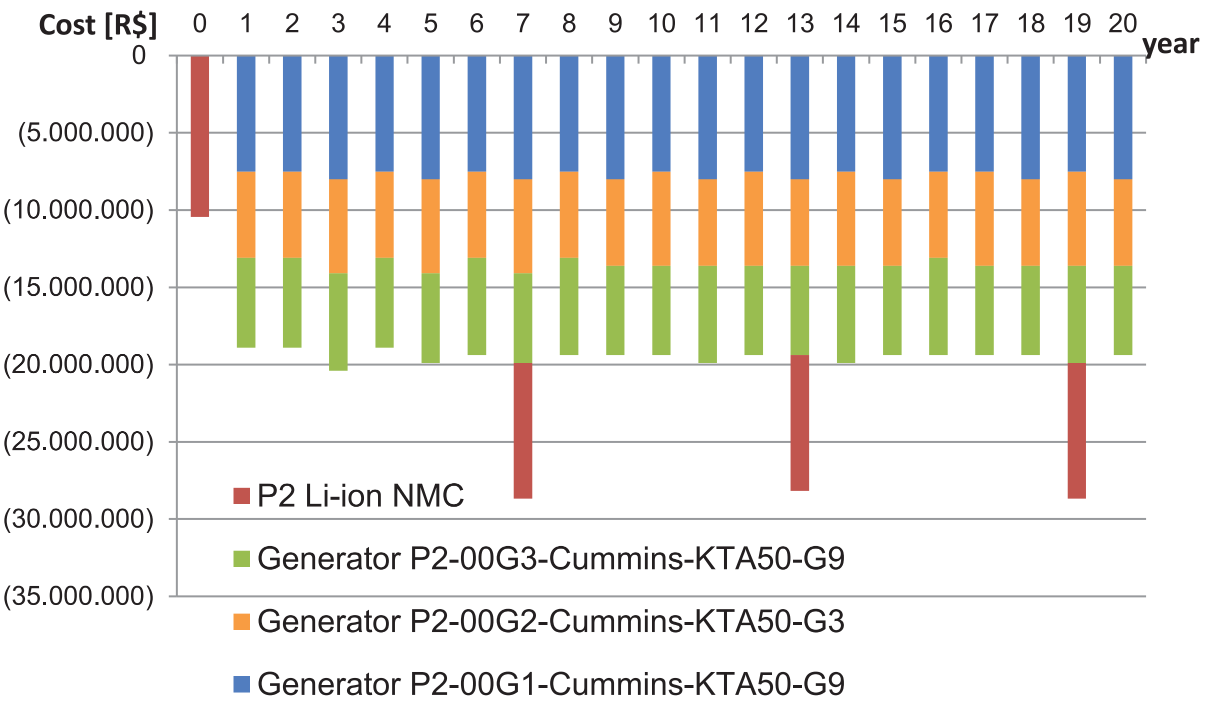
A comparison between the nominal cash flow of the current system and the battery involved system is given in FIGURE 99 and FIGURE 100. Since the PV system already exists and O&M costs are neglected, it does not appear in both figures. There is also no initial investment cost for the diesel generators, because they do already exist. The principal difference in costs between current system and proposed system lies in the investment and replacement costs for the battery system, as shown in FIGURE 99. The variation of generator costs in the base case and the proposed one are caused by lower diesel consumption and less generator run time, due to battery application and total PV integration.

FIGURE 99: PROJECT 2 NOMINAL CASH FLOW WITHOUT BATTERY APPLICATION



SOURCE: The author

FIGURE 100: PROJECT 2 NOMINAL CASH FLOW WITH BATTERY APPLICATION



SOURCE: The author

5.5 SIMULATION PROJECT 3

Peaks of demand and generation lead to overall lower electricity system efficiency and higher costs. Time dependent electricity tariffs are one approach to motivate consumers to peak shifting measures in form of off-peak generation storage for on-peak consumption, which leads to overall demand curve flattening.

The conventional solutions are on the side of the distribution gird operator: grid investment to support the maximum generation and demand peaks and peak generation utilities, which only operate during demand peak hours. For the consumer the white tariff is only attractive, if it leads to cost savings. Therefor the comparative solution is trivial in form of a comparison of the overall consumer electricity cost per kWh of consumed electricity.

In this case, a residential consumer, connected to the low voltage distribution grid and owner of a PV-battery system in an urban region, on the example of São Paulo is analysed. Utilization of a lithium-ion battery with a storage capacity of about 10 kWh and a 2.4 kWp PV system in combination with a monthly demand of 250 kWh or 500 kWh and white tariff conditions. The battery system is used to shift the PV production capacity from the off-peak to the on-peak hours. This way high electricity rates for the consumer and renewable generation peaks as well as demand peaks during on-peak hours are avoided. White tariffs are anticipated by ANEEL regulation n° 733 from 2016, which pretends to start availability for low voltage consumers with monthly consumption rates of 500 kWh or more from 2018 on and for consumption rates equal to or superior to 250 kWh from 2019 on, ANEEL (2016b). The Tariff structures are adopted from ANEEL (2017c) website, where a relation of 1:3:5 is foreseen between the level of electricity cost under off-peak, intermediate and on-peak hours. The sell back rate is presenting the energy exchange, offered by the grid as storage devise for the period of 60 month, whereby the difference between electricity and sellback price is based on the taxes, which are charged for all electricity provided by the grid, independent on overproduction in different hours, compare ANEEL (2012c). An overview of applied electricity tariff data is given in TABLE 46.

TABLE 46: PROJECT 3 WHITE TARIFF CONDITIONS

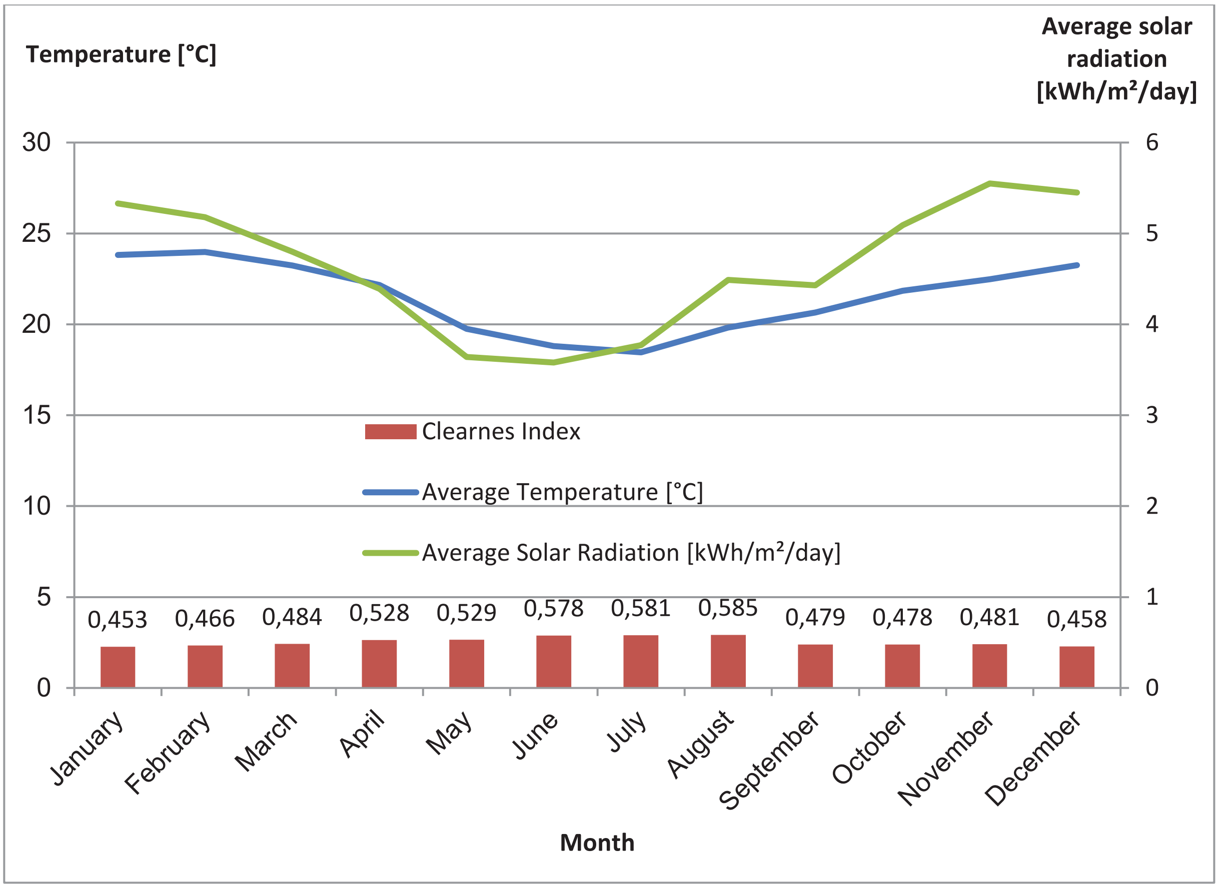
Tariff	Weekday	Day time	Price [R$/kWh]	Sell back [R$/kWh]
Off-Peak	Weekend and on holidays	0am-12pm	0.45	0.30
	Mo-Fr	10pm-4pm		
Intermediate	Mo-Fr	4-5pm & 9-10pm	1.35	0.89
On-Peak	Mo-Fr	5-9pm	2.25	1.48

SOURCE: ANEEL (2017c) and ANEEL (2012c)

The consumer is also operator and owner of the system and principal motivation of operation is electricity cost reduction. Nevertheless, storage size is sufficient to cover a full day demand cycle, what enables intentionally islanding of the consumption unit without lack of supply. Also support of electric vehicle charging can be delivered by the storage system, without interference with the distribution grid. Both advantages are not considered in the simulations but bring additional values to the consumer as well as to the distribution grid operator.

As a representative location of this type of distributed battery application, the capital São Paulo is selected. There are no limitations in terms of regulatory for small scale, residential battery system operation observed. The consumer location is connected to the low voltage distribution grid and suffers no electricity shortage under current demand characteristics. A PV generation capacity is considered, and temperature and solar radiation curves are imported from the NASA open source database. Due to centralized location inside of a huge town, no special costs for transport and access limitations are considered.

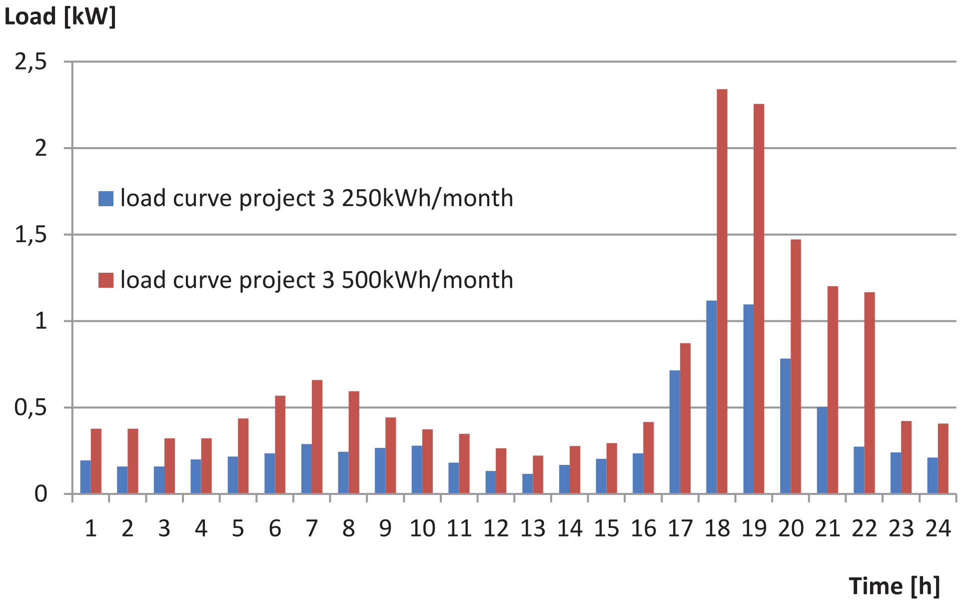
FIGURE 101: PROJECT 3 SOLAR RADIATION AND TEMPERATURE DATA FOR SIMULATION



SOURCE: NASA (2017)

The foreseen white tariff for low voltage consumers, see ANEEL (2017c), in combination with distributed micro generation, see ANEEL (2012c), are applied in combined form in this battery application. The demand curve of the residential consumer is based on the outcomes of a field study on consumer electricity demand, curried out as part of a former R&D project at Institutos Lactec.

FIGURE 102: PROJECT 3 LOAD CURVE FOR 250KWH AND 500KWH MONTHLY CONSUMPTION



SOURCE: The author

The PV system is selected as the same as for project 1 with the only difference in terms of installation price, where a multiplicative factor of two on the module price is used for roof top installation. The total input data for PV is summarized in TABLE 47.

TABLE 47: PROJECT 3 PV SYSTEM SIMULATION DATA INPUT

PV	PV 1
Overall system	
Installed System Power [kWp]	1.5
System Generation [kWh/year]	1,600
General	
Manufacturer	Yingli
Type	Multicrystalline
Name	YL150P-17B
Electrical Bus (AC/DC)	DC
Lifetime [years]	25
Derating Factor [%]	80
Converter	
Ignore dedicated converter	ok
Temperature	
Consider temperature effects	ok
Temperature effects on power [%/°C]	-0,45
Nominal operating cell temperature [°C]	46
Efficiency at standard test conditions [%]	15
Defaults	
Cost table set “P_{max} per module in kW”	0.15
Capital [$] (PV module + mounting structure)	1,100
Replacement [$]	550
O&M [$]	n.c.
Search Space	
Available capacities in kWp	1.5
Ground Reflectance [%]	20
Tracking System	No
Use default slope	Ok
Use default azimuth	Ok

Source: The author

The selected converter types for simulation are from the manufacturer PHB, datasheet available under PHB (2015), and prices are taken from national resellers. The battery converters are not part of this product, but considered as integrant of the li-ion battery system. Nevertheless, to make the simulation program work, a relative rectifier capacity and efficiency are given to the program. All applied converter input data is provided by TABLE 48.

TABLE 48: PROJECT 3 CONVERTER DATA

Converter	Inverter (INV)
General	
Name	PHB1500 / 3000 / 4600
Manufacturer	CE+T
Defaults	
Capacity in kW	
Capital [$]	6,000 / 8,000 / 9,500
Replacement [$]	6,000 / 8,000 / 9,500
O&M [$]	n.c.
Search Space – Size [kW]	
case 1 (consumption 250kWh/month)	1.5
case 2 (consumption 500kWh/month)	
Inverter Input	
Lifetime [years]	15
Efficiency [%]	90
Rectifier Input	
Relative Capacity	100
Efficiency [%]	90

SOURCE: The author

The li-ion battery system data are shown in TABLE 49 and TABLE 50 and are based on measurements published by Impinnisi et al. (2014).

TABLE 49: PROJECT 3 BATTERY SIMULATION DATA INPUT

Battery system data	Battery 1
General	
Manufacturer	Generic
type	Li-ion
Name	P3 Li-ion NMC
Capacity	
Max. Charge Rate [A/Ah]	n.c.
Max. Charge Current / (max. const. Charge Current [A])	120
Max. Discharge Current [A]	320
Other round-trip losses [%]	7.5
Functional Model	
Maximum Capacity [Ah] (calculated)	40.275
Nominal Voltage [V]	3.7
Temperature vs. capacity [%]	
Capacity at -20 °C	95
Capacity at 25 °C	100
Capacity at 55 °C	105
Cycle lifetime (cycles to failure for DoD [%])	
DoD 20 [%]	13,000
DoD 50 [%]	6,500
DoD 80 [%]	3,500
DoD 100 [%]	2,000
Degradation limit for model fitting [%]	
Temperature vs. lifetime (years at temp.)	
lifetime [years] at 20 °C	20
lifetime [years] at 35 °C	20
lifetime [years] at 40 °C	14
lifetime [years] at 45 °C	8
lifetime [years] at 50 °C	4
lifetime [years] at 55 °C	2
lifetime [years] at 60 °C	1
Degradation limit for model fitting [%]	
Thermal	
Max. operating temp. [°C]	60
Min. operating [°C]	-20

SOURCE: Impinnisi et al. (2014)

TABLE 50: PROJECT 3 BATTERY SIMULATION DATA INPUT - CONTINUATION

Battery system data	Battery 1
Lumped thermal model	
Conductance to ambient [W/K]	n.c.
Specific heat capacity [J/kg*K]	n.c.
Defaults	
Quantity	1
Capital [$] ((battery module + housing structure)*1.3)	1,240
Replacement [$] (battery only)	954
O&M [$/year]	n.c.
Search Space	
Site Specific Input	
String Size	5
Initial state of Charge [%]	20
Minimum State of Charge [%]	20
Capacity degradation limit [%]	20
Maintenance Schedule	n.c.

SOURCE: Impinnisi et al. (2014)

The project costs are simulated separately for the two different consumer units with a daily consumption of 8.3 kWh and 16.6 kWh respectively. The battery dimensions are sufficient, to cover the daily consumer demand during intermediate and on-peak hours, from 4pm until 9pm. The PV system dimension is based on a yearly generation level close to the consumer demand, to keep a balanced energy exchange with the grid. The COE for different system constellations are summarized in Table 51.

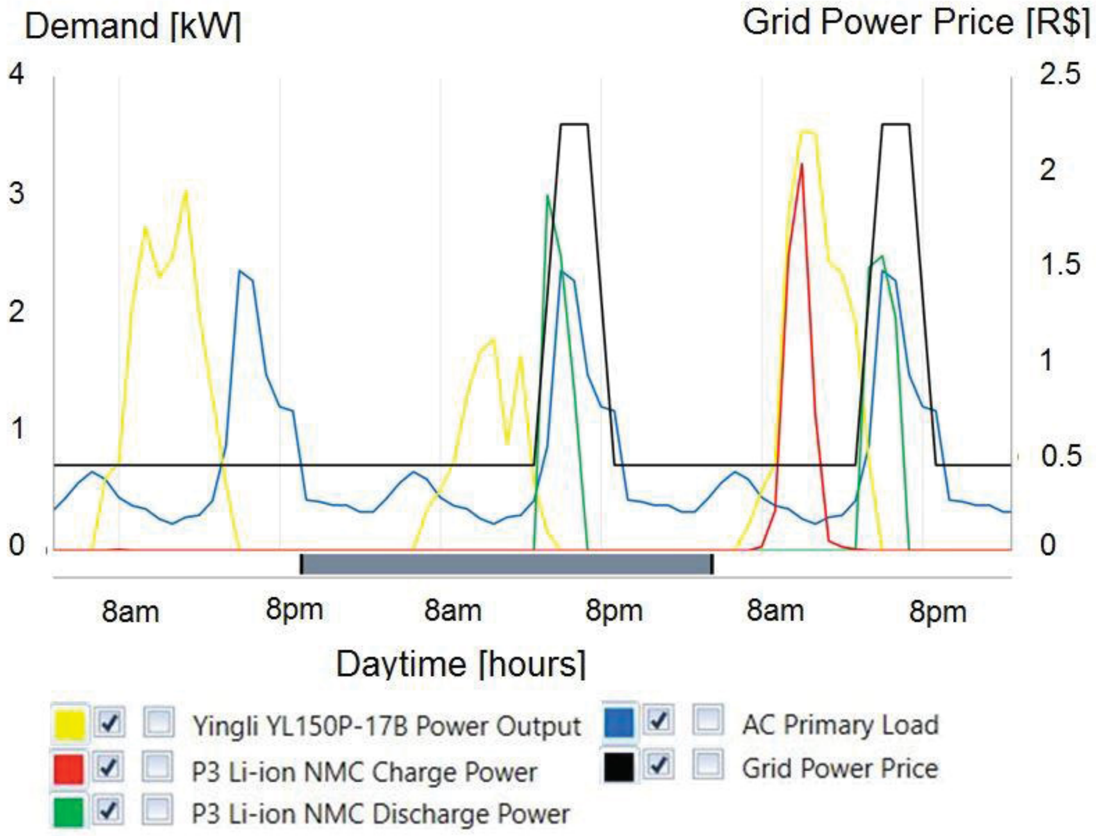
TABLE 51: PROJECT 3 COE OVERVIEW

Electrification system constellation	COE [R$/kWh] Conventional tariff	COE [R$/kWh] White tariff
250kWh/month		
Grid only	0.81	1.01
Grid + PV (2.4kWp)	0.51	0.76
Grid + Battery	1.99 (*)	2.20 (*)
Grid + PV (2.4kWp) + Battery (4.47kWh)	1.08 (*)	1.43
500kWh/month		
Grid only	0.81	1.01
Grid + PV (4.8kWp)	0.47	0.70
Grid + Battery	1.99 (*)	2.09 (*)
Grid + PV + Battery (8.94kWh)	1.08 (*)	1.40

SOURCE: The author *(Life Time Throughput = zero under minimum cost optimization)

Under applied data, in general the conventional tariff shows lower overall electricity costs for both consumer types, whereby the integration of PV brings cost savings of about 40 % under application of the conventional and 25-31 % for the white tariff scenario. For the conventional tariff there is no utilization of the battery system observed, due to the disadvantageous cost structure. Under combination of the white tariff and PV generation, the average electricity cost doubles, compared to the simple on-grid PV system, but the battery is used to supply the consumer demand during on-peak hours, as shown in FIGURE 103 for the 500 kWh/month consumer and white tariff conditions.

FIGURE 103: PROJECT 3 BATTERY OPERATION OBSERVATION

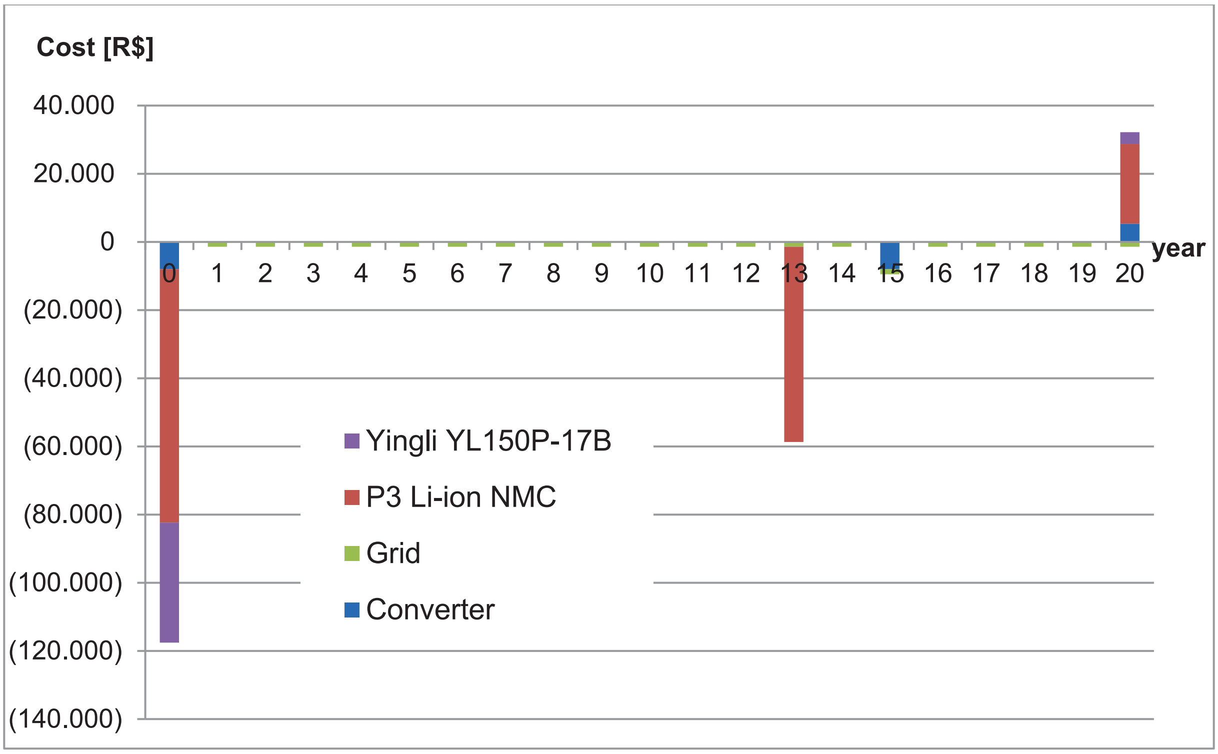


SOURCE: The author

As shown in FIGURE 103, during the weekend, when the lowest electricity tariff is applied, there is no battery discharge observable. Only when the on-peak period starts, the battery gets discharged, to be charged again by the PV system during solar overproduction and so on. Therefore, the application itself seems to work properly to reduce both, on-peak time demand, as well as PV generation peaks and contributes this way to the electricity system stability.

The cost structure is similar for both system sizes and the nominal costs for the larger system is shown in FIGURE 104.

FIGURE 104: PROJECT 3 NOMINAL CASH FLOW FOR 500 KWH/MONTH AND WHITE TARIFF APPLICATION



SOURCE: The author

It is noteworthy, that first: under consideration of different electricity costs, demand curves, hardware type and prices, or PV and battery regulations, this application might show more favouring cost performances. And second: No electricity quality or quantity restrictions for the consumer and the advantages for the distribution grid operators were considered, what might add additionally value to the system and therefor initiate extended remuneration or subsiding measurements between eventual stakeholders.

5.6 SIMULATION PROJECT 4

Captive commercial consumers can choose between different tariff structures, like conventional, blue or green tariff. Depending on the demand distribution in terms of the time of occurrence, blue or green tariffs can bring cost advantages to the consumer. In addition, micro and mini generation can lead to lower overall electricity cost, as well as the application of a storage devise might be used to shift demands from on- to off-peak hours. The combination of PV and battery systems to shift demand appears not only attractive to consumers, but also to distribution grid operators, who suffer from elevated electricity generation costs and quality problems during peak times. The conventional solutions to achieve lower electricity costs can be advantageous selection of electricity tariff or demand side management. For the consumer the investment in PV generation or battery devises is only attractive, if it leads to cost savings. This way, the comparative solution is done in form of a comparison of the overall consumer electricity cost per kWh of consumed electricity, with and without battery utilization.

In this case, a commercial consumer, connected to the medium voltage distribution grid in an urban region, on the example of Belo Horizonte is analysed. A generic lithium-ion battery with a storage capacity of about 50 kWh, in combination with an average daily consumption of 500 kWh and green tariff conditions is analysed. The battery system is used to shift the PV production of a 37 kWp installation from the off-peak to the on-peak hours. This way high electricity rates for the consumer and renewable generation peaks as well as demand peaks during on-peak hours are avoided. The applied green tariff conditions are shown in in Table 52.

TABLE 52: PROJECT 4 GREEN TARIFF CONDITIONS

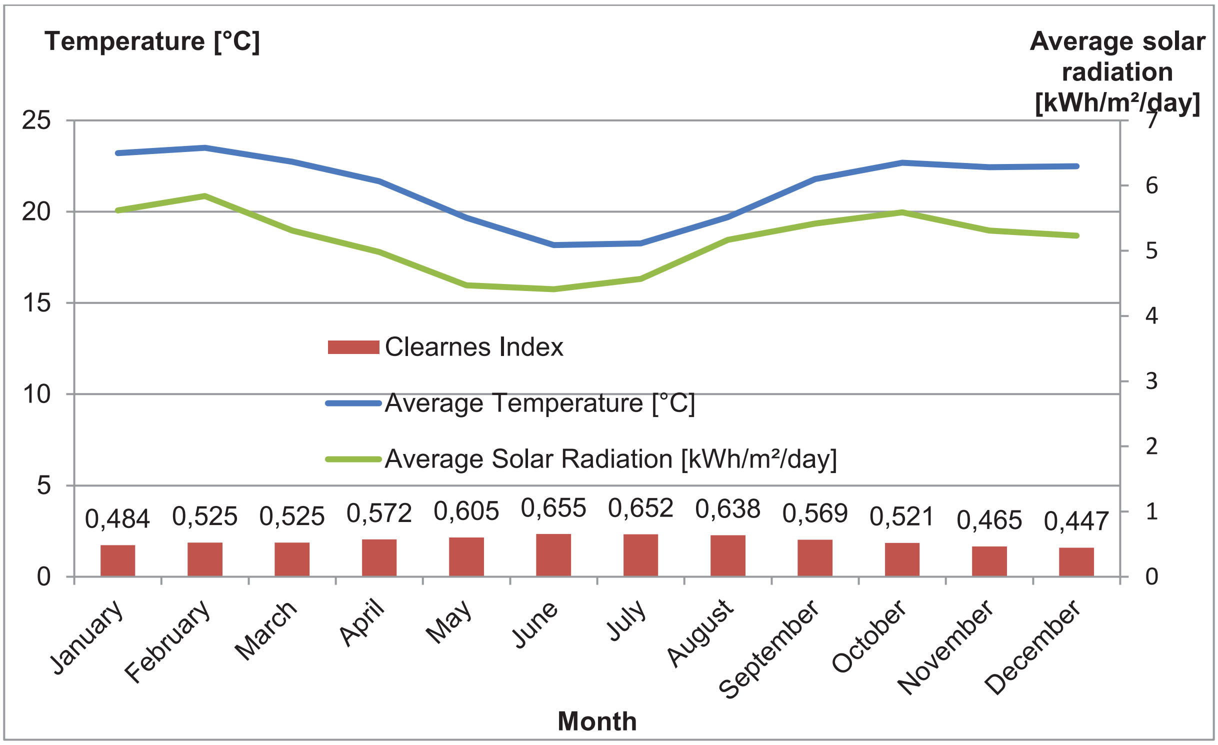
Tariff	Weekday	Day time	Power price [R$/kW]	Price [R$/kWh]	Sell back [R$/kWh]
Off-Peak	Weekend and on holidays	0am-12pm	13.83	0.52	0.34
	Mo-Fr	10pm-4pm			
On-Peak	Mo-Fr	5-9pm		1.87	1.23

SOURCE: CEMIG (2017)

The consumer is also operator and owner of the system and principal motivation of operation is electricity cost reduction, equal to project 3. Nevertheless, storage size is sufficient to cover a full day demand cycle, what enables intentionally islanding of the consumption unit without lack of supply. Also support to fluctuating consumption units, like machines or electric vehicle charging can be delivered by the storage system, without interference with the distribution grid. This way contracted demand rates can be lowered and penalties for overshoot avoided. Both advantages are not considered in the simulations but bring additional values to the consumer as well as to the distribution grid operator.

As a representative location of this type of distributed battery application, the capital of the state Minas Gerais, Belo Horizonte, is selected. There are no limitations in terms of regulatory for commercial battery system operation observed. The consumer location is connected to the medium voltage distribution grid and suffers no electricity shortage under current demand characteristics. A PV generation capacity is considered, and temperature and solar radiation curves are imported from the NASA open source database, see FIGURE 105.

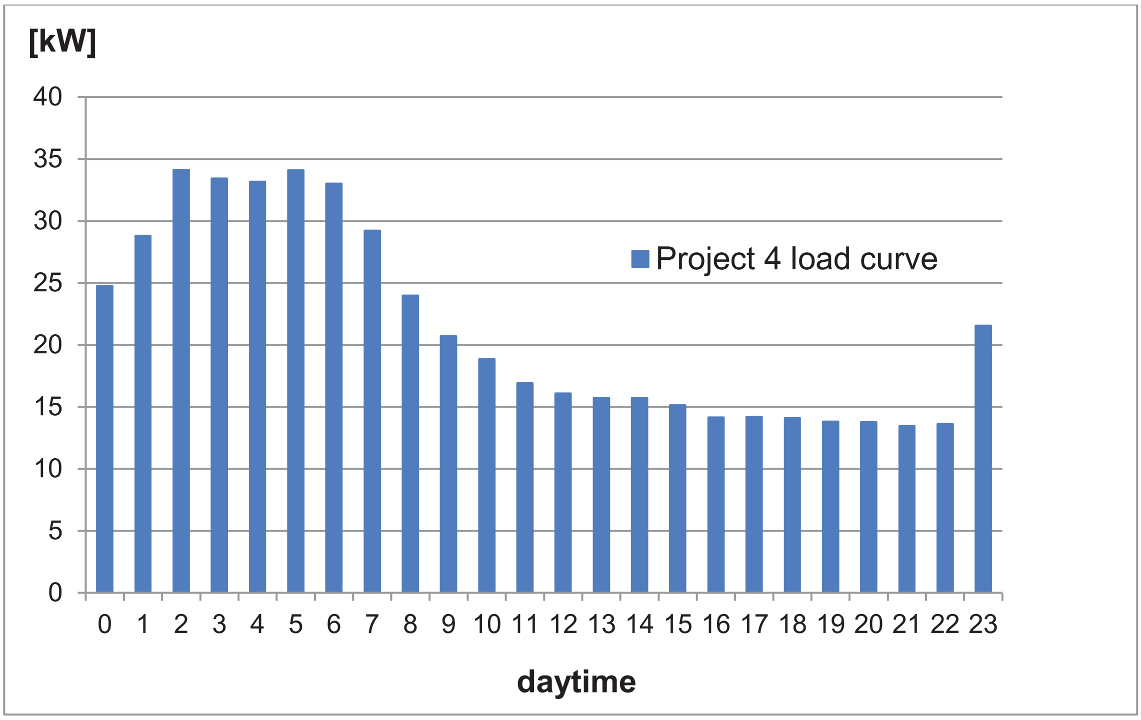
FIGURE 105: PROJECT 4 SOLAR RADIATION AND TEMPERATURE DATA FOR SIMULATION



SOURCE: NASA (2017)

Due to centralized location inside of a huge town, no special costs for transport and access limitations are considered. The demand curve of the commercial consumer is based on measurements in 10-minute time steps with an average load level of 21 kW and a maximal peak load of 47 kW. During the three on-peak hours, the maximal energy consumption is around 50 kWh, what combines with the battery dimension. An exemplary load curve with monthly average values is provided in FIGURE 106.

FIGURE 106: PROJECT 4 LOAD CURVE FOR COMMERCIAL CONSUMER WITH AN AVERAGE DAILY CONSUMPTION OF 500KWH



SOURCE: The author

The PV system is selected as the same as for project 3 but with a peak power of 37 kWp. The selected converter for the simulation is from the manufacturer PHB, datasheet available under PHB (2016), and prices are taken from national resellers. The battery converters are considered as an integrant of the li-ion battery system. But again, to make the simulation program work, a relative rectifier capacity and efficiency are given to the program. All applied converter input data is provided by TABLE 53.

TABLE 53: PROJECT 4 CONVERTER DATA

Converter	Inverter (INV)
General	
Name	PHB20K-DT
Manufacturer	PHB
Defaults	
Capacity in kW	20
Capital [$]	19,000
Replacement [$]	19,000
O&M [$]	n.c.
Search Space – Size [kW]	40
Inverter Input	
Lifetime [years]	15
Efficiency [%]	95
Rectifier Input	
Relative Capacity	100
Efficiency [%]	95

SOURCE: The author

The li-ion battery system data is equal to the simulation in Project 2, except the system size, where a search space of 12 parallel strings of 30 cells each is selected.

The project costs are simulated separately for the three different consumer tariffs. The battery dimensions are sufficient, to cover the daily consumer demand during on-peak hours, from 5pm until 8pm. The PV system dimension is based on a yearly generation level close to the consumer demand, to keep a balanced energy exchange with the grid. The COE for different system constellations are summarized in Table 54.

TABLE 54: PROJECT 4 COE OVERVIEW

Electrification system constellation	COE [R$/kWh] Conventional tariff	COE [R$/kWh] blue tariff	COE [R$/kWh] green tariff
Grid only	0.66	0.62	0.64
Grid + PV	0.63	0.60	0.61
Grid + Battery	0.84 (*)	0.81 (*)	0.82 (*)
Grid + PV + Battery	0.79	0.76	0.75

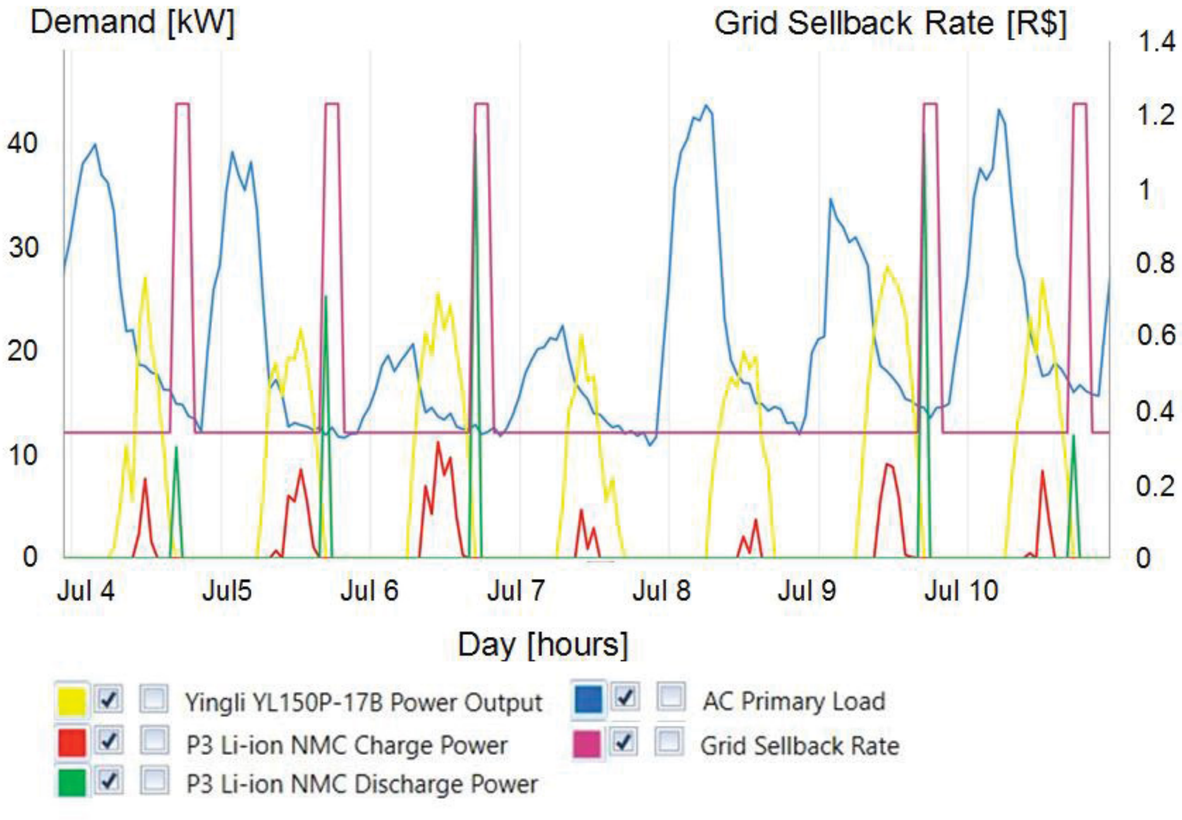
SOURCE: The author *(Life Time Throughput = zero under minimum cost optimization)

Under applied data, in general, the application of a battery system without combination with PV generation is not feasible under cost minimization proposes.

The conventional tariff shows the highest cost level for all observed system constellations. The PV system integration shows minor, but positive cost effects under all analysed tariff conditions.

Under applied hardware costs, the PV-Battery system leads to increasing overall COE in the range of 20 % compared to the grid-only application. The battery gets charged by excess PV generation and discharges during peak time, to lower grid demand or even sell electricity back to the gird in terms of the electricity exchange regulation, when sell back rates are higher. On an exemplary period of one week, the operation scheme of the battery is shown by FIGURE 107.

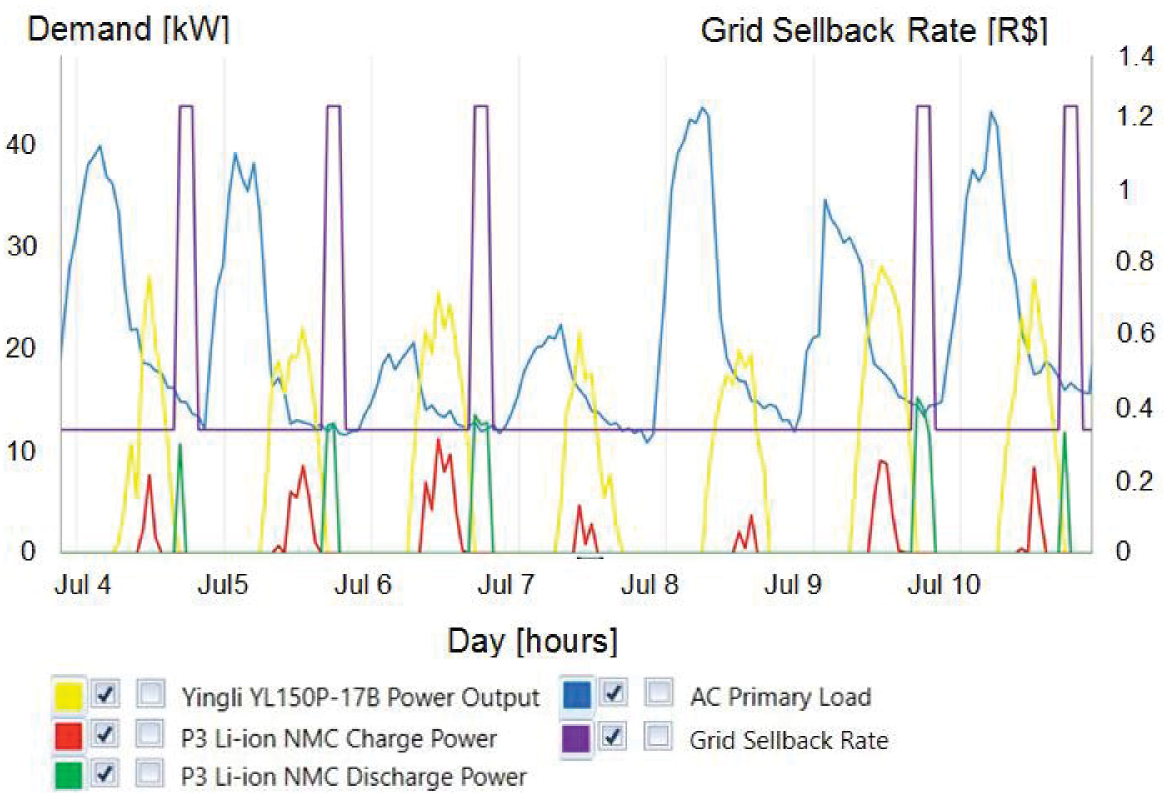
FIGURE 107: PROJECT 4 BATTERY OPERATION OBSERVATION



SOURCE: The author

As shown in FIGURE 107, during the weekend, when there is no peak tariff and elevated sellback rate applied, there is no battery discharge observable. Only when the on-peak period starts, the battery gets discharged, to be charged again by the PV system during solar overproduction, like the white tariff application shown in project 3. Therefore, the application itself seems to work properly to reduce on-peak time demand. Nevertheless, if there was no additional consumption unit, the high electricity purchase rate from the battery can lead to undesired effects to the electricity network. An example of an application, where there is negative consumption, but only compensation until zero consumption desired, is given by FIGURE 108.

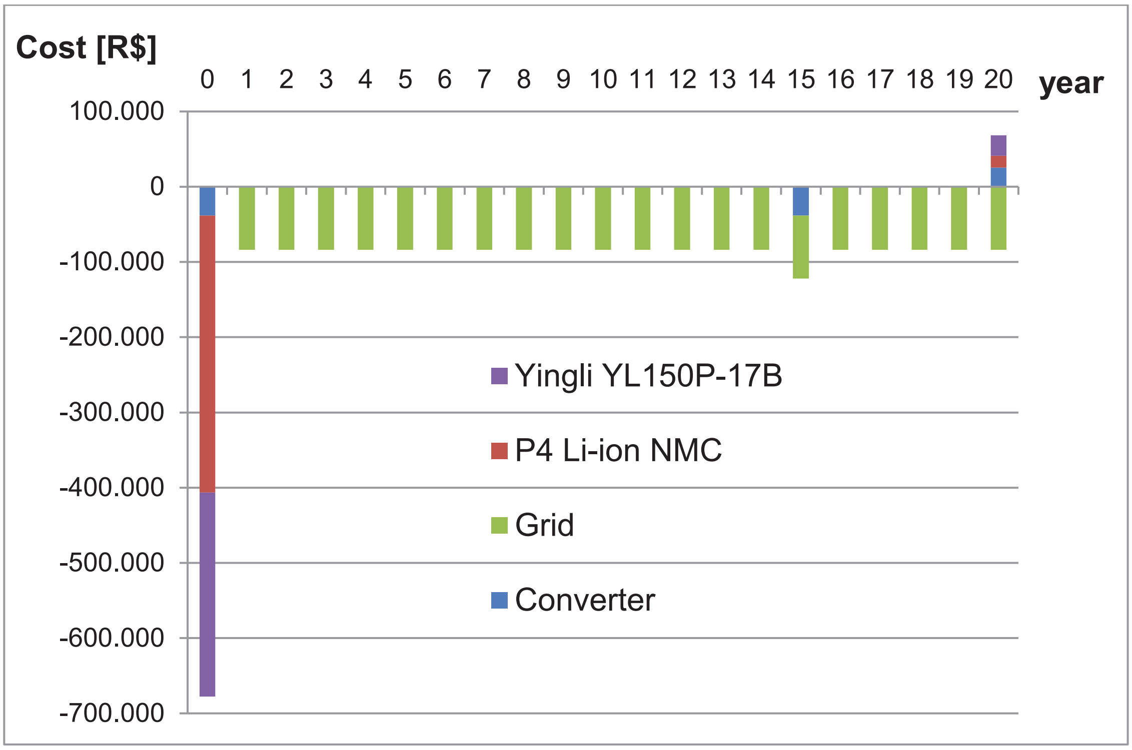
FIGURE 108: PROJECT 4 BATTERY OPERATION WITHOUT NEGATIVE CONSUMPTION RATE BY PV-BATTERY SYSTEM



SOURCE: The author

This way, peak demand as well as peak generation from PV or battery are avoided, what contributes to the electricity system stability. The cost structure is like project 3 and the nominal costs for the larger system are shown in FIGURE 109.

FIGURE 109: PROJECT 4 NOMINAL CASH FLOW FOR 500 KWH/DAY AND GREEN TARIFF APPLICATION



SOURCE: The author

As principal results of on gird battery application for commercial consumers with an overall electricity cost saving target, it is observed that the battery system does not bring positive economic effects to consumer under analysed demand and tariff settings. Nevertheless, there were no peak demand curtailment services to avoid electricity tariff penalties considered. Also, different hardware cost might show more favouring economic performances. Further, there were no electricity quality or quantity restrictions for the consumer and the advantages for the distribution grid operators considered, what might add additionally value to the battery system.

5.7 SIMULATION PROJECT 5

Large scale, fluctuating renewable generation units can lead to grid capacity shortages and quality problems during peak production period and because of fast positive and negative generation ramping. Distribution grid operators need to maintain stable grid operations and meet quality restrictions to avoid system failures and penalties. Peaks of fluctuating generation lead to overall lower electricity quality, efficiency and higher costs, because of increased reserve capacity requirements. At greater distances to the major rotating generation capacity and in higher percentage of the overall grid capacity, the impact on the grid increases and conventional control becomes ineffective.

The fifth simulation is of a lithium ion battery system, used to smoothen the fluctuating and maximal generation peaks of a 500 kWp PV plant, under distribution network capacity limitations. The Storage device with 1,000 kWh and 500 kW is located next to the PV plant, on an endpoint of a large medium voltage line and cloth to a transformer point to the low voltage level. The distribution grid operator applies the battery to compensate the electricity quality problems for the low voltage consumers, caused by the PV plant by limiting and smoothening the generation.

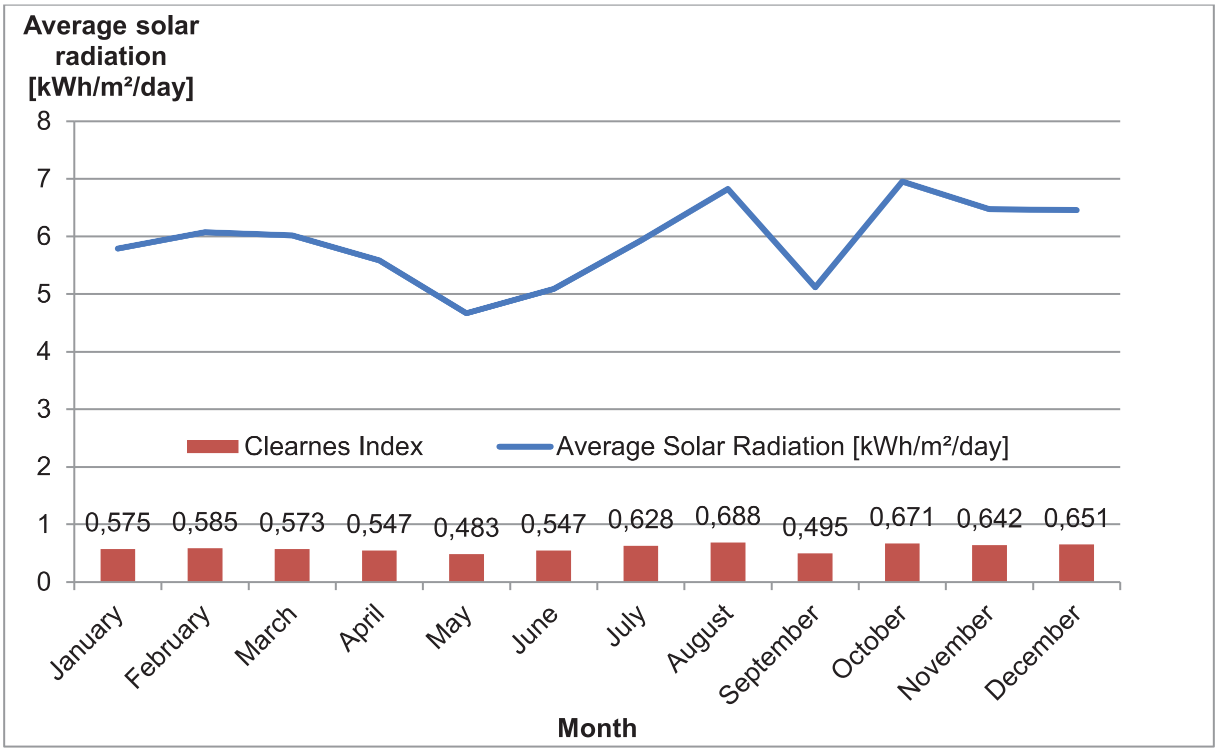
The conventional solutions are grid upgrade and investment in bidirectional transformer stations or PV generation curtailment. To cope with the fast peaks of PV plants, the battery system maximum power needs to be adequate. To limit the maximum power output at any time, the capacity needs to be adjusted. In this example the maximal power is to be limited by 50 % at any time, for which a power to capacity ratio of 500 kW / 1,000 kWh battery system is selected.

The value of the battery application, beside expected improved electricity quality characteristics, is given in form of the additional utilization of the PV generation capacity, exceeding the 50 % of peak power. The distribution grid operator is acting as owner, operator and costumer of the battery as an internal utility. There are no limitations for environmental protection or accessibility of the location for the utilization of a battery system expected, since the installation is beside an existing transformer station. Even so the value of the captured electricity in relation to the time of battery discharge is obvious, the advantages of on peak generation are only limited possible. To be able to capture all excess generation and compensate generation interruption, the storage device needs to be hold cloth to the optimal set point, at any time of potential PV generation.

The regulations ANEEL (2012c) provide the procedures, which controls the connection process for distributed micro and mini generation units. The distribution grid operator needs to attend requests for connection within a strict time schedule and are supposed to offer the cheapest solution for the client, if any constructions therefor are required. For the simulation a solar radiation curve with steps of 1 minute are imported from the open source solar database, available under SODA (2016).

The monthly average values from February 2004 until January 2005 for the selected site location Alto do Rodrigues in the state Rio Grande do Norte, is shown in FIGURE 110.

FIGURE 110: PROJECT 6 SOLAR RADIATION AND CLEARNESS INDEX DATA FOR SIMULATION



SOURCE: SODA (2016)

For the simulations a generic li-ion battery system and converter are applied. All system costs for both, battery and converter are considered with 3,000 R$/kWh inclusive installation and the O&M costs enter with 1 % of the investment. A summary of all applied technical data input is given in TABLE 55.

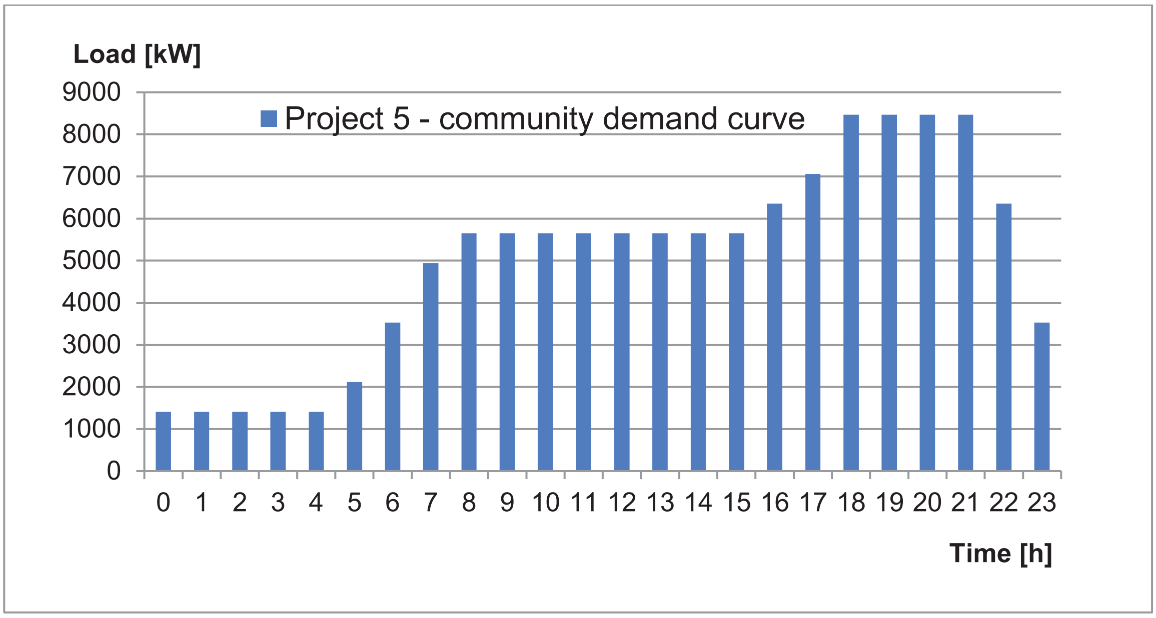
TABLE 55: PROJECT 5 BATTERY SYSTEM DATA

Battery system data	**Battery 1**
General	Generic Li-ion
Capacity [kWh]	1,000
Max. Charge Rate [A/Ah]	n.c.
Max. Charge Current / (max. const. Charge Current [A])	270
Max. Discharge Current [A]	810
Other round-trip losses [%]	8
Functional Model	
Maximum Capacity [Ah] (calculated)	276
Nominal Voltage [V]	3.7
Temperature vs. capacity [%]	
Capacity at -20 °C	84
Capacity at 0 °C	92
Capacity at 40 °C	100
Cycle lifetime (cycles to failure for DoD [%])	
DoD 30 [%]	11,00
DoD 55 [%]	4,500
DoD 70 [%]	3,000
DoD 100 [%]	1,200
Degradation limit for model fitting [%]	20
Temperature vs. lifetime (years at temp.)	15
Degradation limit for model fitting [%]	20
Thermal	
Max. operating temp. [°C]	60
Min. operating [°C]	0
Defaults	
Investment /Reinvestment (incl. converter, control and installation) [R$]	3,000,000
O&M [R$/kWh/year]	30

SOURCE: The author

A generic community load profile with 12,000 kWh daily consumption and 1.8 MW peak, as provided by the simulation program is applied for the simulation. The PV-battery operation is limited to a combined maximal output of 250 kW during the daytime only, between 7am and 7pm. For the battery a setpoint state of charge of 50 % is applied, to guarantee sufficient positive and negative capacity for the PV smoothening. An hourly average demand curve for the community is shown in FIGURE 111.

FIGURE 111: PROJECT 5 LOAD CURVE



SOURCE: The author

The PV system is a generic flat plate one with a maximum power of 500 kWp. The costs are considered with 5,000 R$/kWp inclusive mounting structure and installation and O&M costs are calculated with 50 R$/kWp/year. For calculate the economic performance, the electricity produced by the PV or PV-battery system respectively is rated with 0.53 R$/kWh, conform the conventional low voltage tariff. The results of the simulation of the 500 kWp PV system under maximal power restrictions by the grid of 250 kW, with and without battery operation are shown in Table 56.

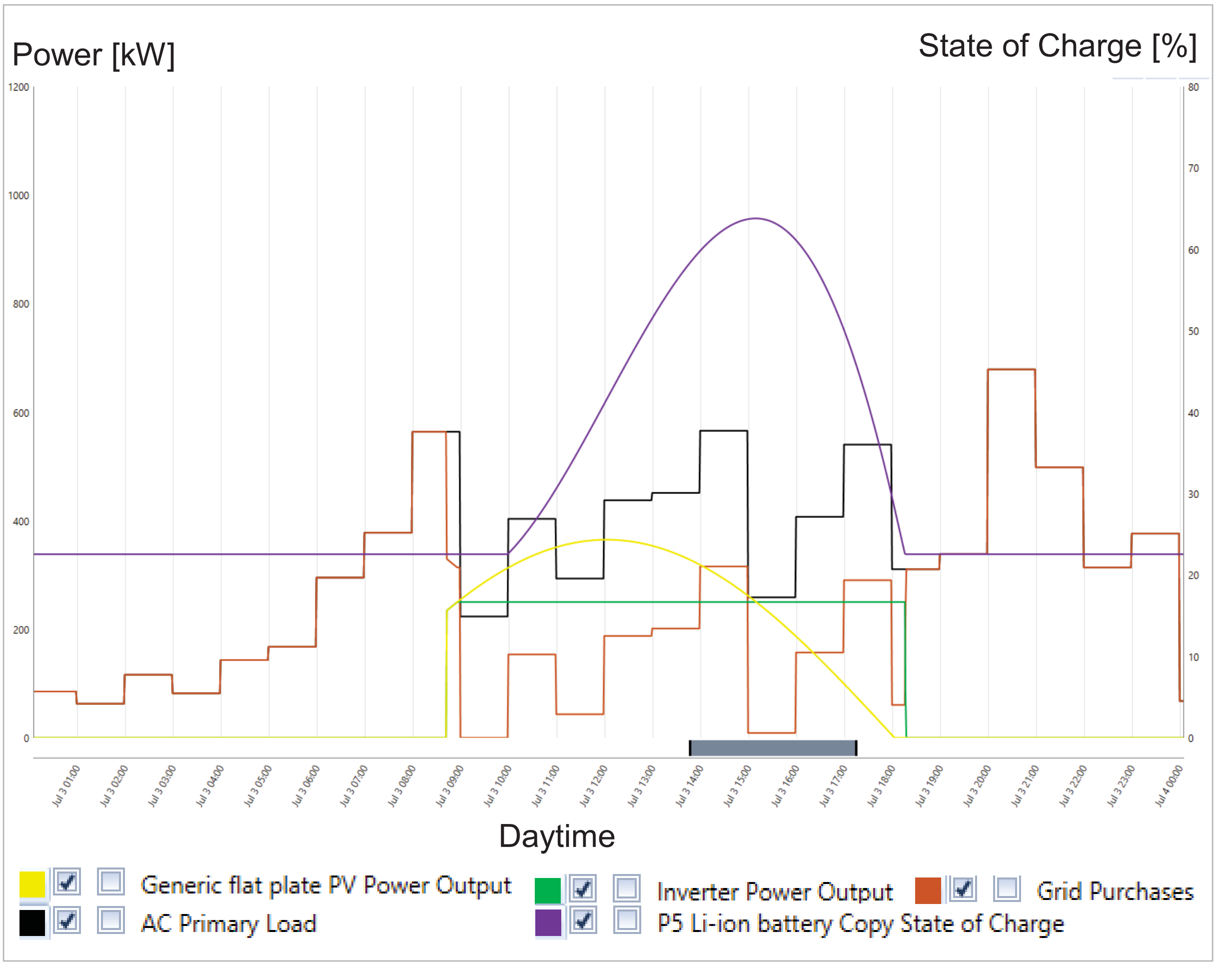
TABLE 56: PROJECT 5 SIMULATION RESULTS PV VS. PV BATTERY SYSTEM

Electrification system constellation	**PV no grid limits**	**PV only**	**PV-battery**
Total electricity purchase for community [kWh/year]	4,380,000	4,380,000	4,380,000
Grid purchase [kWh/year]	3,414,946	3,637,090	3,429,541
PV production [kWh/year]	973,350	973,350	973,350
PV electricity purchase to the grid [kWh/year]	973,350	743,586	743,586
Battery electricity output [kWh/year]			208,249
PV Penetration [%]	22	17	22
Investment cost [R$]	2,500,000	2,500,000	5,500,000
O&M cost [R$/year]	25,000	25,000	55,000
Electricity grid sell [R$/year]		394,101	504,473
Net Present Value (NPV) [R$]	1,166,567	256,976	-2,142,690

SOURCE: The author

Under applied data, in the results show a positive NPV for the conventional operation and still for the operation under limited grid power capacity. The operation of a li-ion battery to smoothen the fluctuating PV generation allows increasing PV electricity use rates, growing from 17 % to 22 % under grid power limitation. The battery shows full capability to capture and shift all PV excess production within a day period. FIGURE 112 shows a random day of PV-battery operation.

FIGURE 112: PROJECT 5 BATTERY OPERATION OBSERVATION



SOURCE: The author

As shown in FIGURE 112, during the peak generation time the PV system releases a constant power of 250 kW, storing the overproduction. From 4pm on, the captured energy is discharged again, maintaining a constant production output. The Battery system is capable to operate within the available capacity ranges, without needs of generation curtailments. A positive economic performance of the studied system is not given under applied assumptions. Nevertheless, under lower grid restrictions and optimized system sizing, including the permission of minor PV curtailments, the results might change drastically. Also, the considered system value for the costumer is only one approach, not considering alternative investments, such as grid reinforcement, which might be avoided or delayed.

5.8 SIMULATION PROJECT 6

Distributed feeders suffer from capacity reduction during elevated temperature peaks due to increased resistance, what requires compensation by local generation enforcement. In case of missing generation capacities, the feeders need to be shut down, what leads to penalty fees for the distribution grid operators, which vary in relation to the duration of the power cut and the quantity and type of affected consumers. Conventional approaches are distributed diesel generators or grid reinforcement, leading to elevated costs for O&M in case of diesel generators and high investment costs and overcapacities during most operating hours.

Simulation 6 shows the application of a Vanadium Redox Flow (FRV) battery system with a storage capacity of 2,000 kWh and 500 kW nominal power, connected to the middle voltage distribution grid at a location with energy quality and availability problems during these electricity system critical peak hours. To avoid that the feeders need to be switched off, the battery systems are scheduled to discharge at a constant power level during critical hours. During night time, when electricity demand and costs are low, the batteries get charged again.

The distribution grid operator is costumer, owner and operator of the battery system, which is used with the objective of cost reduction. The project location is not defined for the exemplary simulation, but the described problematic can be observed in various Brazilian urban areas where there is access to the medium voltage grid with frequent quality and capacity suffers. The applied electricity costs for the distributer are based on the mixed tariff, which results from the overall yearly amount, payed for the contracted generation, divided by the total capacity. This way the applied cost for electricity is calculated as (R$ 11.872.374 / 28.733 GWh) =0.42 [R$/kWh], see TOSO; CARVALHO DIAS (2015). Based on the average cost, as an approach to simulate the impact of time of demand, the daytime is divided in three groups of 8 hours, representing a low, average and elevated electricity purchasing price for the distributer, see TABLE 57.

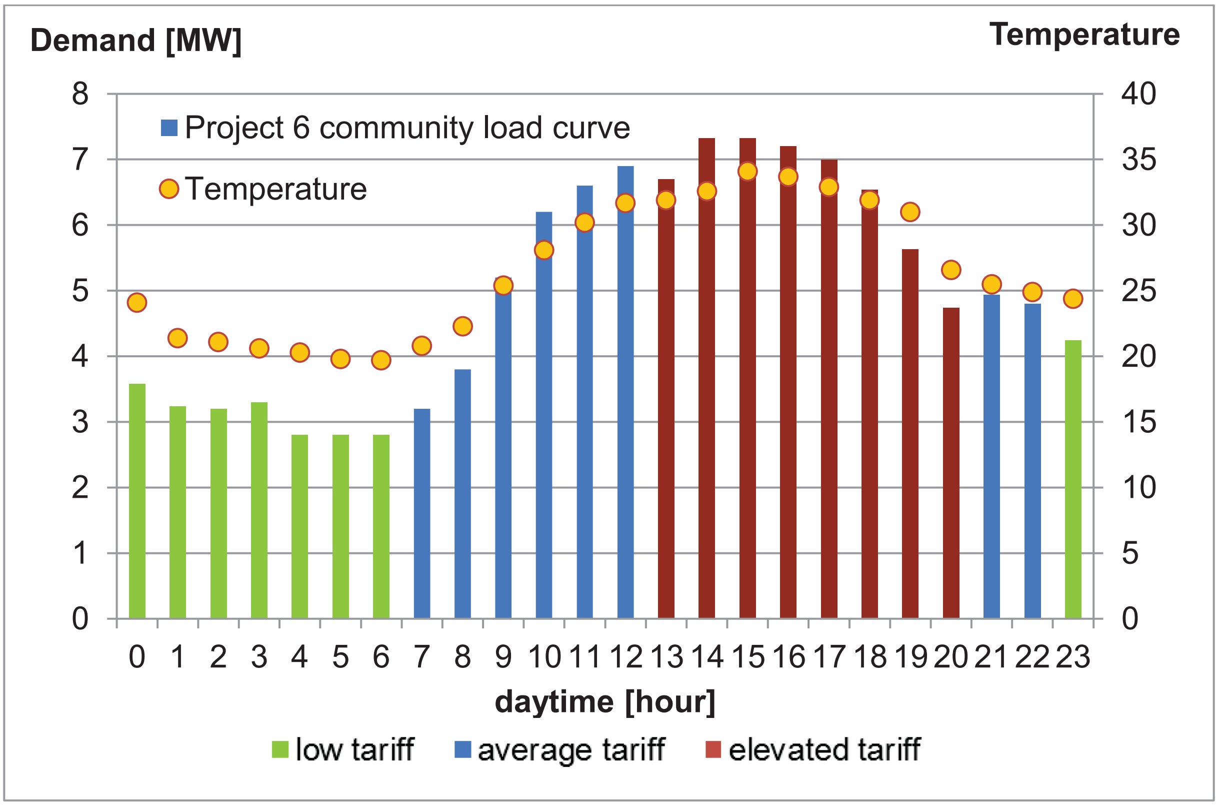
TABLE 57: PROJECT 6 DISTRIBUTION GRID OPERATOR ELECTRICITY COST APPROACH

Cost class	Daytime of electricity purchase	Average electricity purchase cost [R$/kWh]
Low	11pm – 7am	0.25
Average	07am – 02pm & 10pm-11pm	0.42
Elevated	02pm – 10pm	0.50

SOURCE: The author

The applied load curve is adopted from TOSO; CARVALHO DIAS (2015), who analysed the same problem with real demands from a national distribution grid operator. The daily consumption of the analysed feeder with 70 consumer units is 120 MWh see FIGURE 113.

FIGURE 113: PROJECT 6 COMMUNITY LOAD CURVE



SOURCE: Adapted from TOSO; CARVALHO DIAS (2015)

According to the seasonal temperature variations the support generation is provided as shown in TABLE 58.

TABLE 58: PROJECT 6 SUPPORT GENERATION SCHEDULE

Month	Support generation cycles (2-4pm) days per year
October - March	Daily
April & September	5 days per week
May & August	2 days per week
June & July	None

SOURCE: The author

The battery system gets only charged during low electricity cost periods, in the simulations between 11pm and 7am, what brings economic advantages on electricity consumption caused by battery cycle losses. The lacking capacity during critical feeder hours is supplied by a battery system and costs are compared to conventional diesel generation. The analysed VRF battery system is generic and costs are adapted from the outcome of the proposals from the public call “chamada 21”. The Converter is already part of the total battery system, therefor for simulations, there is only a lossless generic converter with a total capacity of 500 kW inserted, to enable simulations. Used battery data for the simulation is shown in TABLE 59.

TABLE 59: PROJECT 6 BATTERY SIMULATION DATA INPUT

Battery system data	Battery 1
General	
Manufacturer	Generic
type	VRF
Name	P6-VRF
Capacity [kWh]	2,000
Max. Charge Rate [A/Ah]	n.c.
Max. Charge Current / (max. const. Charge Current [A])	480
Max. Discharge Current [A]	480
Round Trip Efficiency [%]	70
Functional Model	
Nominal Voltage [V]	800
Defaults	
Quantity	1
Capital [$] (overall battery system inclusive converter and installation)	8,000,000
Replacement [$] (battery only)	6,000,000
O&M [$/year] (1% of hardware cost)	60,000
Search Space	
Site Specific Input	1
String Size	n.c.
Initial state of Charge [%]	0
Minimum State of Charge [%]	0
Lifetime	20

SOURCE: The author

Since the battery system is an internal component of the distribution grid operator and used to improve electricity supply rates and quality, there are no restrictions by the electricity market regulations expected, as long as economic viability is given. The sensitivity to electricity tariffs is not relevant for the principal application, studied by this analysis. Nevertheless, the battery system is utilized for only two hours per day from 2pm until 4pm for feeder support and might be used for further applications like peak shifting in form of arbitrage trading in addition.

For the comparison with the diesel generator, a generic diesel generator is applied. Input data for simulations are shown in TABLE 60.

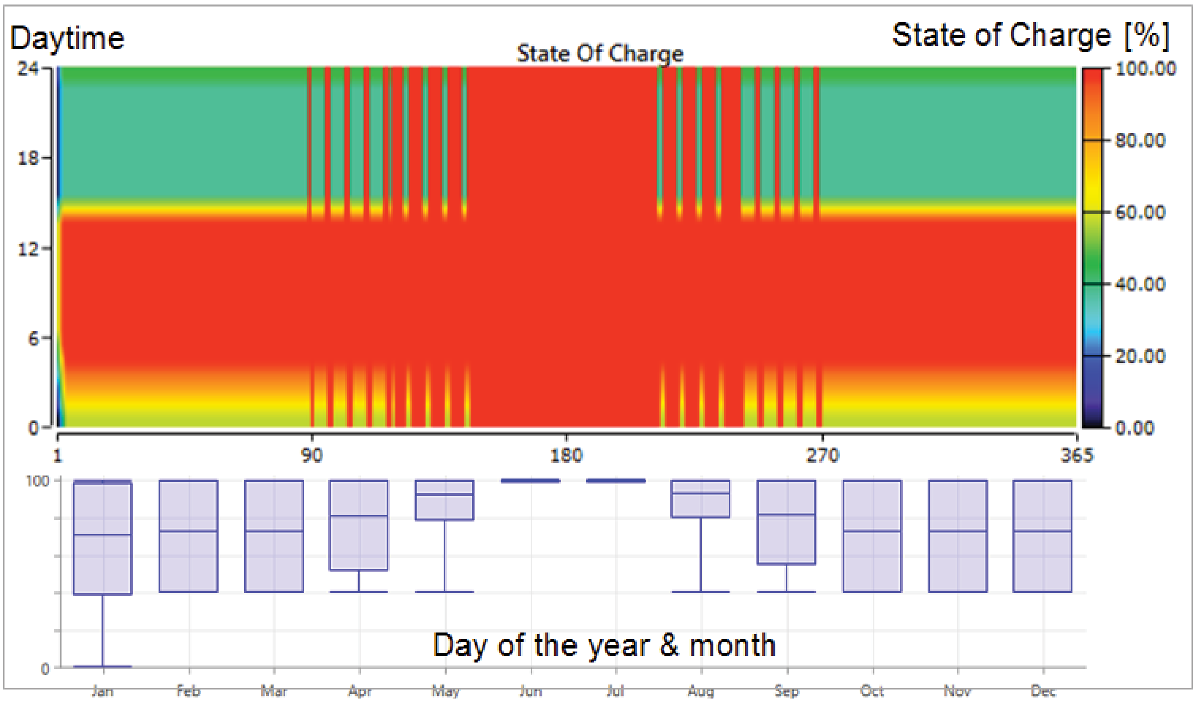
TABLE 60: PROJECT 6 DIESEL GENERATOR SIMULATION DATA

Generator	1
Name	P6-Diesel Generator 500kW
Manufacturer	Generic
Minimum Load Ratio [%]	25
Lifetime [Hours]	15,000
Minimum Runtime [Minutes]	112
Fuel	
Reference generator active capacity [kW]	100
Fuel Curve	
Slope [L/hr/kW output]	0.253
Costs	
Capacity (kW)	500
Capital [R$]	250,000
Replacement [R$]	250,000
O&M [R$/hour]	2
Fuel Resource	
Diesel Fuel Price [R$/L]	2.5

SOURCE: The author

The simulated operation scheme of the battery system is shown in the FIGURE 114 in terms of charging and discharging time and state of charge over the period of one year.

FIGURE 114: PROJECT 6 VRF BATTERY STATE OF CHARGE



SOURCE: The author

During coldest month, June and July, the battery stays in floating mode and increases operation frequency until begin of October, where the daily operation mode starts.

Under presented conditions and considerations, the simulations show the following operational characteristics and results, as compared in TABLE 61, between operation without generation support and with diesel generator or battery system integration.

TABLE 61: PROJECT 6 STATUS QUO VS. DIESEL GENERATOR VS. BATTERY UTILIZATION RESULTS

System characteristics	Status Quo	With diesel generator	With battery system
Feeder shut downs / support generations [days/year]	239	239	239
Support generation differed (2 hours 500kW) [MWh/year]		239	239
Not delivered Electricity during feeder off time [MWh/day]	14.65		
Lost electricity sales [R$/day]	6,153		
Yearly sales losses [R$/year]			
Low tariff time (0.25 R$/kWh)	875,338		
Average tariff time (0.42 R$/kWh)	1,470,567		
Elevated tariff time (0.50 R$/kWh)	1,750,675		
Investment cost for support generation [R$]		250,000	8,000,000
O&M, fuel and cycle efficiency electricity cost [R$/year]		167,746	85,657
Annualized generation system costs [R$/year]		188,690	764,027
Marginal generation costs [R$/kWh]		0.63	0.36
Annualized generation cost [R$/kWh]		0.80	3.20
Operation hours / full cycles		9,560	2,857
Average cost for purchased electricity on feeder [R$/kWh]	0.42	0.43	0.47
Net Present Value (discount rate 12%) [R$]			
NPV (low tariff) [R$]	-6,538,288	5,035,319	-2,101,522
NPV (average tariff) [R$]	-10,984,317	9,481,348	2,344,507
NPV (elevated tariff) [R$]	-13,076,568	11,573,599	4,436,758

SOURCE: The author

The principal observation of the application of feeder support generation is the leverage effect of a relatively small additional generation support of 500 kW, which guarantees the delivery of a much greater electricity demand of 7.4 MW. These ways the economics are not only based on the minor additional generation output, but on the overall available power, which in this case is over 14 times higher. This way under consideration of a discount rate of 12 % the diesel generator shows positive NPVs for all electricity sell back tariffs. The battery system has a negative NPV if the electricity sellback tariff is equal to the charging price but becomes positive, if there is a higher value for the delivering time considered. To reach a neutral NPV the battery investment cost would need to go down to R$ 5.9 million under constant framework conditions.

5.9 ANALYSIS OF RESULTS AND DISCUSSION

Summing up the overall simulation results the following conclusions can be taken:

- Technically the battery storage systems meet all operational requirements
- Arbitrage or Peak shift applications with time dependent tariffs show no positive economic balance for analysed demand curves
- PV-battery systems compared to pure PV operation show higher overall electricity costs due to battery investment costs higher than fees for grid exchange rates.
- Battery applications, prepending generation reduction or interruption are favourable due to their lever effect of minor additional investment for overall generation emittance.

The specific simulation results, as presented directly after the simulations, in terms of economics, are only valid for the respective ownership and remuneration model. Even if technically the same operation with identical hardware occurs, the viability might change significantly in relation to the operation objective, the location, the opportunity costs etc. The economics are influenced by various parameters and cost performance is sensitive to minor changes. Therefor each application requires a specific analysis, to study and consider the entire system behaviour. The created method proved to be one possibility to realize this study, following the flowcharts stepwise.

6 CONCLUSIONS AND FUTURE WORKS

Along this thesis the available battery technologies and applications have been studied. Starting with a general overview on global scale, based on the energy storage database from the US American department of energy, which give information about realized and planned projects. The identified main technologies are lead acid, lithium ion, vanadium redox flow (VRF), sodium, nickel and metal air batteries. Lithium-ion represent the highest market share in terms of project quantity, capacity and power, followed by sodium batteries. VRF and lead acid show constant representation over the last 10 years, whereby li-ion and sodium batteries are covering over 90 % of the investments in 2016.

The main techno economic characteristics for stationary battery systems, beside investment cost, lifetime and round-trip efficiency, are minimal state of charge, sensitivity of cycle life due to discharging depth and temperature, maximal charge and discharge currents and cell voltage. In comparison, lithium-ion batteries show highest roundtrip efficiency rates but also high investment cost. Sodium batteries have lower efficiency rates due to high thermal losses in standby operation. VRF systems show advantages in terms of simple capacity upgrade but depending on operation mode show elevated losses caused by electricity consumption for pumping. Lead acid batteries are characterised by low investment costs but poor cycle life and high minimum state of charge. Metal air batteries are still in the beginning of the development phase and efficiency rate as well as cycle life are still superior to competitive technologies.

To identify the relevant structure and regulations for distributed battery applications, the Brazilian electricity system was analysed in terms of main actors, electricity trade, tariffs and selected regulations, such as for distributed generation or rural electrification. The Brazilian hydro power electricity system is unique in its kind and characterized by numerous institutions for control and optimization of hydro resources and power supply.

The principal actors of the electricity market are generator, transmission grid operators, distribution grid operators, traders and consumers. In general, the market can be divided in a captive and a free sector. The captive consumers are supplied by the distribution grid operators and get access to different tariffs depending of consumer type, location and demand whereby distributers consumers Free consumers can choose between national standardized captive tariffs or direct purchase from traders or generators. Generators can sell their capacity on auctions to the distribution grid operators, to supply the captive market or undertake direct bilateral contracts with traders or major free consumers.

Controlled by the Brazilian Electricity Regulatory Agency the market actors need to follow numerous regulations in relation to generation, transmission, distribution and operation. Some of the relevant regulations for distributed battery applications are n° 482 and 687 for distributed mini and micro generators, n °493 for proceedings and conditions for generation and distribution within isolated micro systems and n °488, establishing the conditions for universalization of electricity distribution services in rural areas. These regulations are identified as principal incentives for consumers or distribution grid operators to invest in distributed battery applications, to lower electricity costs or as an alternative to conventional electrification methods.

The literature review about the state of the art of battery technologies, applications and business models showed two principal messages. First, there are plenty of possible applications for several battery technologies, such as Li-ion, lead acid, VRF, Znbr, ZEBRA, NaS or NiCd to just name the most relevant, bringing positive technical impact on the analysed systems. These include in principal isolated electrification in combination with renewable generation, integration of renewable generation to the grid, ancillary and quality services to the distribution grid, self-consumption increase or arbitrage operation. And second, the complex environment for business models, including market structures, owner ship models, economic regulations and alternative technologies, methods and approaches, acting in the same area as storage. Based on the multi-dimensional environment for the application of distributed battery a method was developed, which combines in general the terms a business model, project environment, electricity market, battery system hardware and a simulation tool, which are interconnected with each other.

The public call “chamada 21” from the Brazilian Electricity Regulatory Agency was evaluated and a roadmap for distributed battery application in Brazil for the next four years designed. Based on the information of 29 project proposals for about 70 pilot plants with 13 different ESS technologies in 25 applications, a classification into 6 main groups of different battery systems in terms of battery technology, capacity, grid connection, voltage level, combination with generation units and application was built.

Finally, the developed method is applied, to create a complete business model for one project of each of the six identified battery project classes. The main characteristics and results of these projects are:

- System 1 is off-grid rural residential electrification, with a PV-battery system, realized by the distribution grid operator. For the analysed OPzS or lead carbon batteries the economic viability is competitive to diesel generation.
- System 2 analyses the use of a li-ion battery system to minimize diesel consumption and increase renewable generation integration in an isolated micro grid, operated in MV level. The battery system is owned by the distribution grid operator and brings reduced diesel consumption even shown increased overall electricity costs.
- System 3 is for a residential consumer, connected to the low voltage distribution grid and owner of a PV-battery system in an urban region. The lithium-ion battery with a storage capacity of about 10 kWh and a 2.4 kWp PV system are operated white tariff conditions to analyse overall electricity costs. The battery system contributes to the electricity quality by shifting the PV production capacity from the off-peak to the on-peak hours but economical the application is not attractive for the consumer.
- System 4 studies the application of a li-ion battery with a capacity equal to the on-peak demand of a commercial consumer, connected to the medium voltage distribution grid in combination with a PV plant. The consumer is owner and operator of the battery system to lower electricity costs by shifting peak consumption to off-peak hours with the battery system in combination with hour-seasonal tariffs. The cost performance is negative for the analysed tariff conditions, even so the application improves electricity quality in the system.
- System 5 is a simulation of a 1,000 kWh and 500 kW lithium ion battery system, at MV level, used to smoothen the fluctuating and maximal generation peaks of a 500 kWp PV plant, under distribution

network capacity limitations. The distribution grid operator is owner and operator to smoothen the fluctuating PV generation under grid capacity limitations at an end point. Technically the battery is capable to keep the PV generation within the permitted levels and an increase of PV generation capacity use can be realized. Considering only the additional PV generation as basis for economy calculations, the application shows a negative NPV.

- Simulation 6 shows the application of a Vanadium Redox Flow (FRV) battery system, connected to the middle voltage distribution grid with energy quality and availability problems during electricity system critical peak hours. The distribution grid operator applies the battery generation capacity during critical hours to avoid feeder shut downs. The Battery system shows a negative NPV, if electricity costs during charging time are considered equal to discharging time and under application of a return of invest rate of 12 %. Under consideration of electricity rates 60 % higher during critical hours than during charging hours, NPV already becomes positive. The calculations are done neglecting the additional cost saving for improved electricity supply rates, which are under observation of ANEEL.

Future works:

- A detailed study of electricity market regulations in relation to distributed battery application.
- A detailed operational optimization of all single cases of distributed battery application.
- Consideration of benefits for thermo-electric power plants under battery operation for electricity quality applications.
- Identify how politicians and regulatory agencies can support the introduction of battery systems to the distribution network.

REFERENCES

ABRADEE. .Disponível em: <www.abradee.com.br>.

ANEEL. RESOLUÇÃO NORMATIVA Nº 493, DE 5 DE JUNHO DE 2012. , p. 9, 2012a. Disponível em: <https://www.google.com.br/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0ahUKEwiRg9iFwq7TAhVFDJAKHc9lD8cQFggkMAA&url=http%3A%2F%2Fwww.aneel.gov.br%2Fcedoc%2Fren2012493.pdf&usg=AFQjCNGhgRRwRehQbqlhypJ-6hAc1BBrhQ&cad=rja>.

ANEEL. Resolução normativa n°488, de 15 de maio de 2012. , 2012b. Disponível em: <https://www.google.com.br/search?q=aneel+488&ie=utf-8&oe=utf-8&client=firefox-b&gws_rd=cr&ei=8YT2WM3-PMyHwgTk34i4BA>.

ANEEL. RESOLUÇÃO NORMATIVA Nº 482, DE 17 DE ABRIL DE 2012. , p. 9, 2012c.

ANEEL. **Cadernos Temáticos ANEEL Micro e Minigeração Distribuída Sistema de Compensação de Energia Elétrica**. Brasília, 2016a.

ANEEL. RESOLUÇÃO NORMATIVA Nº 733, DE 06 DE SETEMBRO DE 2016. , 2016b. Disponível em: <https://www.google.com.br/url?sa=t&rct=j&q=&esrc=s&source=web&cd=4&cad=rja&uact=8&ved=0ahUKEwjg76751N7TAhUCkpAKHTOOA5QQFgg-MAM&url=http%3A%2F%2Fwww2.aneel.gov.br%2Faplicacoes%2Faudiencia%2Farquivo%2F2013%2F043%2Fresultado%2Fren2016733.pdf&usg=AFQjCNFwB8i7C2AtW7_SuYcB5Vt4vRffxw>.

ANEEL. ANEEL. Disponível em: <http://www.aneel.gov.br/>.

ANEEL. ANEEL - List of Distributers. Disponível em: <http://www2.aneel.gov.br/aplicacoes/links/Default_Detail.cfm?idLinkCategoria=14 >.

ANEEL. ANEEL tarifa branca. Disponível em: <http://www.aneel.gov.br/tarifa-branca>.

ANEEL-SPE; RUFINO, R. D.; PEPITONE DA NÓBREGA, A.; et al. CHAMADA NO 021 / 2016 PROJETO ESTRATÉGICO: 'ARRANJOS TÉCNICOS E COMERCIAIS PARA A INSERÇÃO DE SISTEMAS DE ARMAZENAMENTO DE ENERGIA NO SETOR ELÉTRICO BRASILEIRO'. , 2016. Brasília: Agência Nacional de Energia Elétrica – ANEEL Superintendência de Pesquisa e Desenvolvimento e Eficiência Energética – SPE. Disponível em: <www.aneel.gov.br/documents/656831/14944744/Chamada+PD_Estrategico_21_Armazenamento_Julho2016/60026e38-1859-4a34-b528-9965715cba65?version=1.0>.

ANEEL R&D - lei nº 9.991/2000. .Disponível em: <http://www2.aneel.gov.br/area.cfm?idArea=722&idPerfil=3>.

ANUTA, O. H.; TAYLOR, P.; JONES, D.; MCENTEE, T.; WADE, N. An international review of the implications of regulatory and electricity market structures on the emergence of grid scale electricity storage. **Renewable and Sustainable Energy Reviews**, v. 38, p. 489–508, 2014. Elsevier. Disponível em: <http://dx.doi.org/10.1016/j.rser.2014.06.006>.

BATTKE, B.; SCHMIDT, T. S. Cost-efficient demand-pull policies for multi-purpose technologies – The case of stationary electricity storage. **Applied Energy**, v. 155, p. 334–348, 2015. Elsevier Ltd. Disponível em: <http://dx.doi.org/10.1016/j.apenergy.2015.06.010>.

BATTKE, B.; SCHMIDT, T. S.; GROSSPIETSCH, D.; HOFFMANN, V. H. A review and probabilistic model of lifecycle costs of stationary batteries in multiple applications. **Renewable and Sustainable Energy Reviews**, v. 25, p. 240–250, 2013. Elsevier. Disponível em: <http://dx.doi.org/10.1016/j.rser.2013.04.023>.

BCB. Banco Central do Brasil. Disponível em: <http://www.bcb.gov.br/pt-br/#!/home>.

BECKER, A.; BERTHOLD, A.; AG, A. B. B.; CONREDER, A.; AG, E. E. B. **Batteriespeicher in der Nieder- und Mittelspannungsebene**. 2015.

BEHRANGRAD, M. A review of demand side management business models in the electricity market. **Renewable and Sustainable Energy Reviews**, v. 47, p. 270–283, 2015. Elsevier. Disponível em: <http://dx.doi.org/10.1016/j.rser.2015.03.033>.

BRADBURY, K.; PRATSON, L.; PATIÑO-ECHEVERRI, D. Economic viability of energy storage systems based on price arbitrage potential in real-time U . S . electricity markets. **Applied Energy**, v. 114, p. 512–519, 2014. Elsevier Ltd. Disponível em: <http://dx.doi.org/10.1016/j.apenergy.2013.10.010>.

CAPES. CAPES PERIODICOS. Disponível em: <http://www.periodicos.capes.gov.br/>.

CARRASCO, L. M.; NARVARTE, L.; MARTÍNEZ-MORENO, F.; MORETÓN, R. In-field assessment of batteries and PV modules in a large photovoltaic rural electrification programme. **Energy**, v. 75, 2014.

CE+T. Media: 1.5kVA Inverter. , 2017. Disponível em: <http://www.cet-power.com/en/products/modular-inverters/media>.

CEMIG. CEMIG Electricity Tariffs. Disponível em: <http://www.cemig.com.br/pt-br/atendimento/Paginas/valores_de_tarifa_e_servicos.aspx>.

COPEL. COPEL. Disponível em: <www.copel.com>.

CPUC. Self Generation Incentive Program. Disponível em: <http://www.cpuc.ca.gov/General.aspx?id=5935>.

DOE. **Electric Power Industry Needs for Grid-Scale Storage Applications**. 2010.

EDP. .Disponível em: <http://www.edp.com.br/distribuicao/edp - escelsa/informacoes/comerciais/tabela-do-calculo-pis-pasep-confins/Paginas/default.aspx>.

EOS. EOS Energy Storage. Disponível em: <http://www.eosenergystorage.com/products/>.

ERPI; RASTER, D. **Electricity Energy Storage Technology Options: A White Paper on Applications, Costs, and Benefits.** 2010.

FERREIRA LOPES, H.; GARDE, R.; FULLI, G.; KLING, W.; LOPES PECAS, J. Characterisation of electrical energy storage technologies. **Energy**, v. 53, p. 288–298, 2013. Elsevier Ltd. Disponível em: <http://dx.doi.org/10.1016/j.energy.2013.02.037>.

FOXON, T. J. A coevolutionary framework for analysing a transition to a sustainable low carbon economy. **Ecological Economics**, v. 70, n. 12, p. 2258–2267, 2011. Elsevier B.V. Disponível em: <http://dx.doi.org/10.1016/j.ecolecon.2011.07.014>.

GARCHE, J. (ED.). **Encyclopedia of electrochemical power sources**. 1st ed. Elsevier, 2009.

GARIMELLA, N.; NAIR, N. C. Assessment of Battery Energy Storage Systems for Small-Scale Renewable Energy Integration. TENCON 2009 - 2009 IEEE Region 10 Conference. **Anais...** . p.1–6, 2009. TENCON 2009 - 2009 IEEE Region 10 Conference. Disponível em: <http://ieeexplore.ieee.org/document/5395831/>.

Global-Rates.com. .Disponível em: <http://de.global-rates.com/wirtschaftsstatistiken/inflation/verbraucherpreisen/vpi/brasilien.aspx>.

HIGGINS, A.; GROZEV, G.; REN, Z.; et al. Modelling future uptake of distributed energy resources under alternative tariff structures. **Energy**, v. 74, n. C, p. 455–463, 2014. Elsevier Ltd. Disponível em: <http://dx.doi.org/10.1016/j.energy.2014.07.010>.

Homer Energy. .Disponível em: <http://www.homerenergy.com/>.

IEA-ETSAP IRENA. **Renewable Energy Integration in Power Grids**. 2015.
IEEE. ., 2017. Disponível em: <https://www.ieee.org/index.html>.

IMPINNISI, P. R.; WANICK, C.; ANDRADE, J. DE; CAMARGO, C. A. Aplicabilidade de baterias em sistemas de armazenamento de energia na baixa tensão. Políticas Energéticas para a Sustentabilidade. **Anais...** . p.12, 2014. Florianópolis: IXCBPE Congresso Brasileiro de Planejamento energético.

INSTITUTOS LACTEC. **Elaboração de Metodologia de Suprimento de Energia Elétrica a Sistemas Isolados no Pantanal Sul-Matogrossense -MACROETAPA 4 – DIAGNÓSTICO DE ATENDIMENTO E - ETAPA 14. Vetores Técnicos e Análise de Viabilidade Econômica ENTREGA 45: Relatório parcial 2 – Me**. 2016.

IRENA. Recommendations for policy makers on designing auctions. IRENA. **Anais...** . p.A presentation made by Rabia Ferroukhi in workshop, 2013. Abu Dhabi.

KÄRKKÄINEN, S. **Integration of Demand Side Management , Distributed Generation , Renewable Energy Sources and Energy Storages**. 2008.

KEAR, G.; SHAH, A. A.; WALSH, F. C. Development of the all - vanadium redox fl ow battery for energy storage : a review of technological , fi nancial and policy aspects. **International Journal of Energy Research**, , n. May 2011, p. 1105–1120, 2011.

KFW. KFW Erneuerbare Energien Speicher KRedit 275. , 2016. Disponível em: <https://www.kfw.de/inlandsfoerderung/Unternehmen/Energie-Umwelt/Förderprodukte/Erneuerbare-Energien-—-Speicher-(275)/>.

KORTHAUER, R. **Handbuch Lithium-Ionen- Batterien**. 2013.

KRIEGER, E. M.; CANNARELLA, J.; ARNOLD, C. B. A comparison of lead-acid and lithium-based battery behavior and capacity fade in off-grid renewable charging applications. **Energy**, v. 60, p. 492–500, 2013. Elsevier Ltd. Disponível em: <http://dx.doi.org/10.1016/j.energy.2013.08.029>.

MANCHESTER, S.; BARZEGAR, B.; SWAN, L.; GROULX, D. Energy storage requirements for in-stream tidal generation on a limited capacity electricity grid. **Energy**, v. 61, p. 283–290, 2013. Elsevier Ltd. Disponível em: <http://dx.doi.org/10.1016/j.energy.2013.08.036>.

MANZ, D.; KELLER, J.; MILLER, N. Value Propositions for Utility-Scale Energy Storage. Power Systems Conference and Exposition (PSCE). **Anais...** . p.1–10, 2011. Disponível em: <http://ieeexplore.ieee.org/document/5772524/?section=abstract>.

MOSELEY, P. T.; GARCHE, J. **Electrochemical Energy Storage for Renewable Sources and Grid Balancing**. 2015.

NAGANO. Nagano Diesel Generator NG3200 Manual. , 2017. Disponível em: <http://www.naganoprodutos.com.br/novosite/canais/produtos/vitrine.asp?codProduto=486>.

NASA. Surface Meteorology and Solar Energy - NASA. Disponível em: <https://eosweb.larc.nasa.gov/sse/>.

NERY, E. **MERCADOS E REGULAÇÃO DE ENERGIA ELÉTRICA**. Rio de Janeiro: Cigré-Brasil, 2012.

NORGAARD, R. B. **Development Betrayed: The End of Progress and a Coevolutionary Revisioning of the Future**. Routledge, 1994.

NOTTROTT, A.; KLEISSL, J.; WASHOM, B. Energy dispatch schedule optimization and cost benefit analysis for grid-connected , photovoltaic-battery storage systems.

Renewable Energy, v. 55, p. 230–240, 2013. Elsevier Ltd. Disponível em: <http://dx.doi.org/10.1016/j.renene.2012.12.036>.

NYKAMP, S.; ANDOR, M.; HURINK, J. L. ‘ Standard ’ incentive regulation hinders the integration of renewable energy generation. **Energy Policy**, v. 47, p. 222–237, 2012. Elsevier. Disponível em: <http://dx.doi.org/10.1016/j.enpol.2012.04.061>.

NYKAMP, S.; BAKKER, V.; MOLDERINK, A.; HURINK, J. L.; SMIT, G. J. M. Break-even analysis for the storage of PV in power distribution grids. **International Journal of Energy Research**, v. 38, n. 9, p. 1112–1128, 2014. Disponível em: <http://dx.doi.org/10.1002/er.3106>.

PAINE, N.; HOMANS, F. R.; POLLAK, M.; BIELICKI, J. M.; WILSON, E. J. Why market rules matter: Optimizing pumped hydroelectric storage when compensation rules differ. **Energy Economics**, v. 46, p. 10–19, 2014. Elsevier B.V. Disponível em: <http://dx.doi.org/10.1016/j.eneco.2014.08.017>.

PAINE, N.; HOMANS, F. R.; POLLAK, M.; BIELICKI, J. M.; WILSON, E. J. Why market rules matter : Optimizing pumped hydroelectric storage when compensation rules differ. **Energy Economics**, v. 46, p. 10–19, 2014. Elsevier B.V. Disponível em: <http://dx.doi.org/10.1016/j.eneco.2014.08.017>.

PAVLOV, D. **Lead-Acid Batteries: Science and Technology**. 2011.

PHB. PHB Solar inverter datasheet. , 2015. Disponível em: <http://www.phb.com.br/produtos/solar/inversores/1500W_br.aspx>.

PHB. PHB20K-DT Solar Inverter Datasheet. , 2016. Disponível em: <http://www.phb.com.br/PDFs/Produtos/Solar/Inversores/InversoresTrifasicosPHB.pdf>.

PIETILA, A.; BEAUSOLEIL-MORRISON, I.; NEWSHAM, G. R. Zero peak housing : Exploring the possibility of eliminating electrical draws from houses during periods of high demand on the electrical grid. **Building and Environment**, v. 58, p. 103–113, 2012. Elsevier Ltd. Disponível em: <http://dx.doi.org/10.1016/j.buildenv.2012.06.019>.

PLASMATRONICS. PL20 Charge Controller. , 2017. Disponível em: <https://www.google.com.br/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwj40ayw6abTAhWGjZAKHaVqBXYQFggkMAA&url=http%3A%2F%2Fwww.plasmatronics.com.au%2Fdownloads%2FPLRef6.2.0.pdf&usg=AFQjCNFvnDoqB9htk3oeARwa4EIwrfhiyw>.

POMPER, D. **Watts the future holds: structuring and regulating electricity storage markets to benefit ratepayers**. 2011.

POUDINEH, R.; JAMASB, T. Distributed generation , storage , demand response and energy efficiency as alternatives to grid capacity enhancement. **Energy Policy**, v. 67, p. 222–231, 2014. Elsevier. Disponível em: <http://dx.doi.org/10.1016/j.enpol.2013.11.073>.

POULLIKKAS, A. A comparative overview of large-scale battery systems for electricity storage. **Renewable and Sustainable Energy Reviews**, v. 27, p. 778–788, 2013. Elsevier. Disponível em: <http://dx.doi.org/10.1016/j.rser.2013.07.017>.

Purdue Engineering. .Disponível em: <https://engineering.purdue.edu/ViPER/research.html#lithium >.

REINER KORTHAUER ET AL. **Handbuch Lithium-Ionen-Batterien**. Berlin, Heidelberg: Imprint: Springer Vieweg, 2013.

REN21. **Renewables 2016 Global Status Report**. Paris, 2016.

SANDIA NATIONAL LABORATORIES. DOE global energy storage database. Disponível em: <http://www.energystorageexchange.org/>.

Science Direct. .Disponível em: <http://www.sciencedirect.com/>.

SODA. SODA - Solar Energy Services for Professionals. Disponível em: <http://www.soda-is.com/eng/services/services_radiation_free_eng.php>.

Springer. .Disponível em: <http://link.springer.com/>.

STERNER, M.; STADLER, I. **Energiespeicher - Bedarf, Technologien, Integration**. Berlin, Heidelberg: Springer Berlin Heidelberg, 2014.

STRBAC, G. Demand side management : Benefits and challenges. **Energy Policy**, v. 36, p. 4419–4426, 2008. Disponível em: <http://www.sciencedirect.com/science/article/pii/S0301421508004606>.

SUKKAR, T.; SKYLLAS-KAZACOS, M. Water transfer behaviour across cation exchange membranes in the vanadium redox battery. , v. 222, p. 235–247, 2003. Disponível em: <www.sciencedirect.com/science/article/pii/S0376738803003090/pdfft?md5=ffaf89dd30b6010097cf6e56e0b826f7&pid=1-s2.0-S0376738803003090-main.pdf>.

TAN, X.; LI, Q.; WANG, H. Advances and trends of energy storage technology in Microgrid. **International Journal of Electrical Power and Energy Systems**, v. 44, n. 1, p. 179–191, 2013. Elsevier Ltd. Disponível em: <http://dx.doi.org/10.1016/j.ijepes.2012.07.015>.

TAYLOR, P.; BOLTON, R.; STONE, D.; et al. **Pathways for energy storage in the UK Authors**. 2012.

TAYLOR, P. G.; BOLTON, R.; STONE, D.; UPHAM, P. Developing pathways for energy storage in the UK using a coevolutionary framework. **Energy Policy**, v. 63, p. 230–243, 2013. Elsevier. Disponível em: <http://dx.doi.org/10.1016/j.enpol.2013.08.070>.

TOSO, L. D.; CARVALHO DIAS, M. M. **AVALIAÇÃO DE SISTEMAS DE**

ARMAZENAMENTO DE ENERGIA NA DISTRIBUIÇÃO PARA ALÍVIO DE SOBRECARGAS, 2015. Universidade Federal do Paraná.

TURKER, B.; KLEIN, S. A.; HAMMER, E.; LENZ, B.; KOMSIYSKA, L. Modeling a vanadium redox flow battery system for large scale applications. **Energy Conversion and Management**, v. 66, p. 26–32, 2013. Disponível em: <http://dx.doi.org/10.1016/j.enconman.2012.09.009>.

VASCONCELOS, J.; RUESTER, S.; HE, X.; CHONG, E.; GLACHANT, J.-M. **Electricity Storage : How to Facilitate its Deployment and Operation in the EU**. 2012.

WAGNER-SOLAR. Solaranlagenportal. Disponível em: <https://www.solaranlagen-portal.com/photovoltaik/betrieb/aufstaenderung>.

VAN WERVEN, M. J. N. VAN; SCHEEPERS, M. J. J. The changing role of distribution system operators in liberalised and decentralising electricity markets. Power Systems International Conference. **Anais...** . p.1–6, 2005. Amsterdam. Disponível em: <http://ieeexplore.ieee.org/document/1600532/?reload=true>.

WICKLEIN, R. C. Designing for appropriate technology in developing countries. , v. 20, p. 371–375, 1998.

YINGLI SOLAR. Yingli YL150P-17B. , 2017. Disponível em: <https://www.google.com.br/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=0ahUKEwjw067i9KLTAhVDhZAKHUgpAo0QFggrMAE&url=https%3A%2F%2Fwww.neosolar.com.br%2Floja%2Ffileuploader%2Fdownload%2Fdownload%2F%3Fd%3D0%26file%3Dcustom%252Fupload%252FFile-1464893875.pdf&usg=AFQjCNFSvHMTAqXorj5g66zZQK8-23Q9xw&cad=rja>.

ZACKRISSON, M.; AVELLÁN, L.; ORLENIUS, J. Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles – Critical issues. **Journal of Cleaner Production**, v. 18, n. 15, p. 1519–1529, 2010. Disponível em: <http://www.sciencedirect.com/science/article/pii/S0959652610002167>. Acesso em: 4/4/2013.

ZHU, JINGWEI, MICHAEL Z. Q. CHEN, B. DU. A new pricing scheme for controlling energy storage devices in future smart grid.(Research Article)(Report).PDF. **Journal of Applied Mathematics**, v. 2014, n. Article ID 340842, p. 11, 2014. Hindawi Publishing Corporation. Disponível em: <https://www.hindawi.com/journals/jam/2014/340842/>.

ANNEX

Annex 1:

ANNEX 1: DOE GLOBAL ENERGY STORAGE DATABASE – CRITERIA

DOE Global Energy Storage Database - Criteria
Project Name
Technology Type
Technology Type Category 1
Technology Type Category 2
Rated Power in kW
Duration at Rated Power HH:MM
Status
Service/Use Case 1
Service/Use Case 2
Service/Use Case 3
Service/Use Case 4
Service/Use Case 5
Service/Use Case 6
Service/Use Case 7
Service/Use Case 8
Service/Use Case 9
Service/Use Case 10
Service/Use Case 11
Service/Use Case 12
Latitude
Longitude
City
State/Province
Country
Street Address
Zip/Mail Code
Description
Web Link
Announcement Date
Construction Date
Commissioning Date
Decommissioning Date
ISO/RTO
Utility
Utility Type
Grid Interconnection
Paired Grid Resource
Ownership Model
Equity Owner 1
Equity Owner 1 Percentage
Equity Owner 2
Equity Owner 2 Percentage

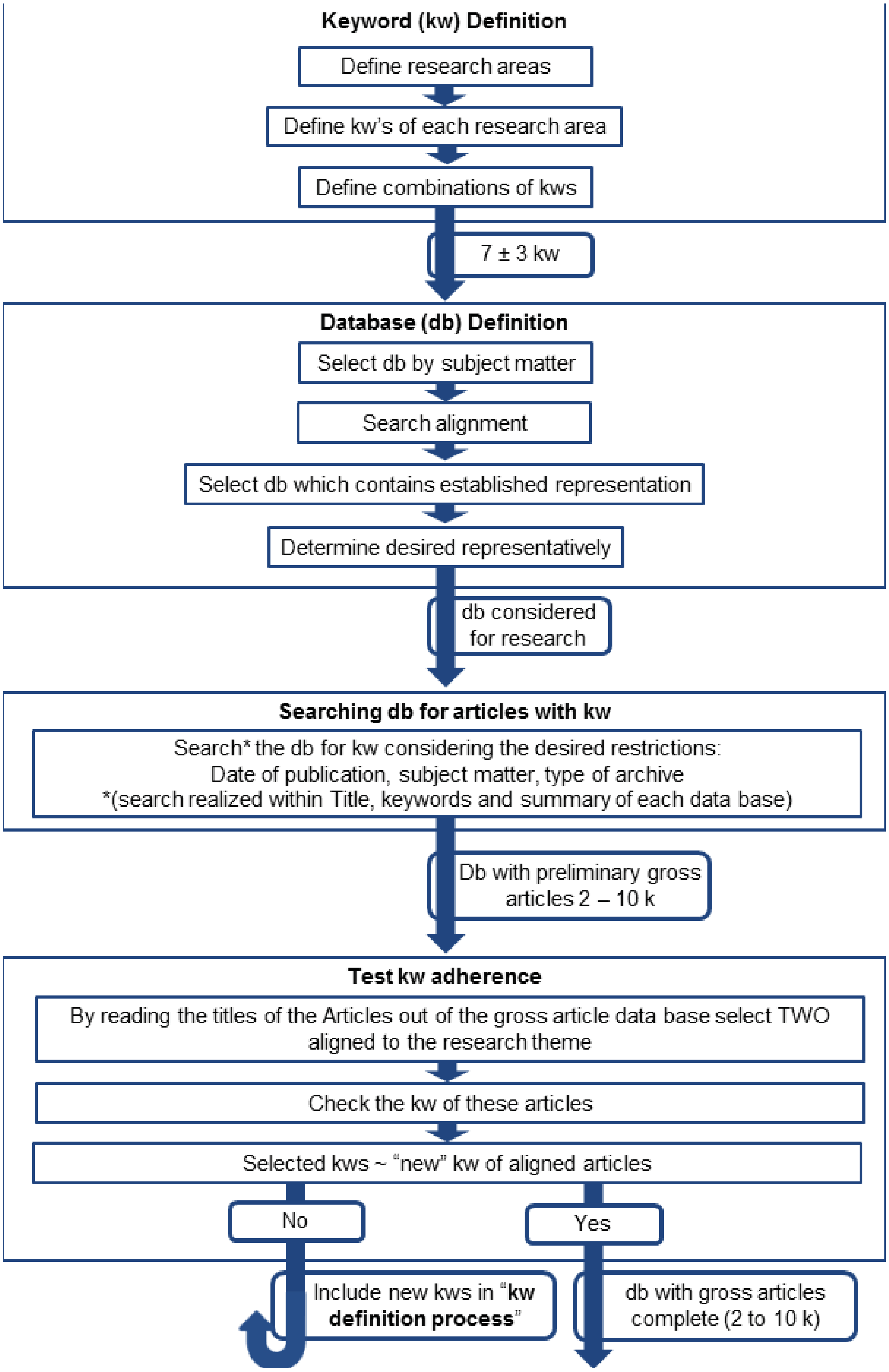
Energy Storage Technology Provider
Power Electronics Provider
Integrator Company
O&M Contractor
Developer
EPC 1
EPC 2
EPC 3
Debt Provider
Projected Project Lifetime years
Performance
CAPEX $
OPEX $/kWh Capacity/Year
Funding Source 1
Funding Source Details 1
Funding Amount 1
Funding Source 2
Funding Source Details 2
Funding Amount 2
Funding Source 3
Funding Source Details 3
Funding Amount 3
Research Institution
Research Description
Research Institution Link
Contact Name
Contact Email
Contact Phone
Contact Street Address
Contact City
Contact State/Province
Contact Zip/Mail Code
Contact Country
Record Created
Last Updated
Black Start
Electric Supply Reserve Capacity - Non-Spinning
Electric Supply Reserve Capacity - Spinning
Load Following (Tertiary Balancing)
Ramping
Voltage Support
Electric Energy Time Shift
Electric Supply Capacity
Transmission Congestion Relief
Transmission Support
Renewables Capacity Firming
Distribution upgrade due to solar
Distribution upgrade due to wind

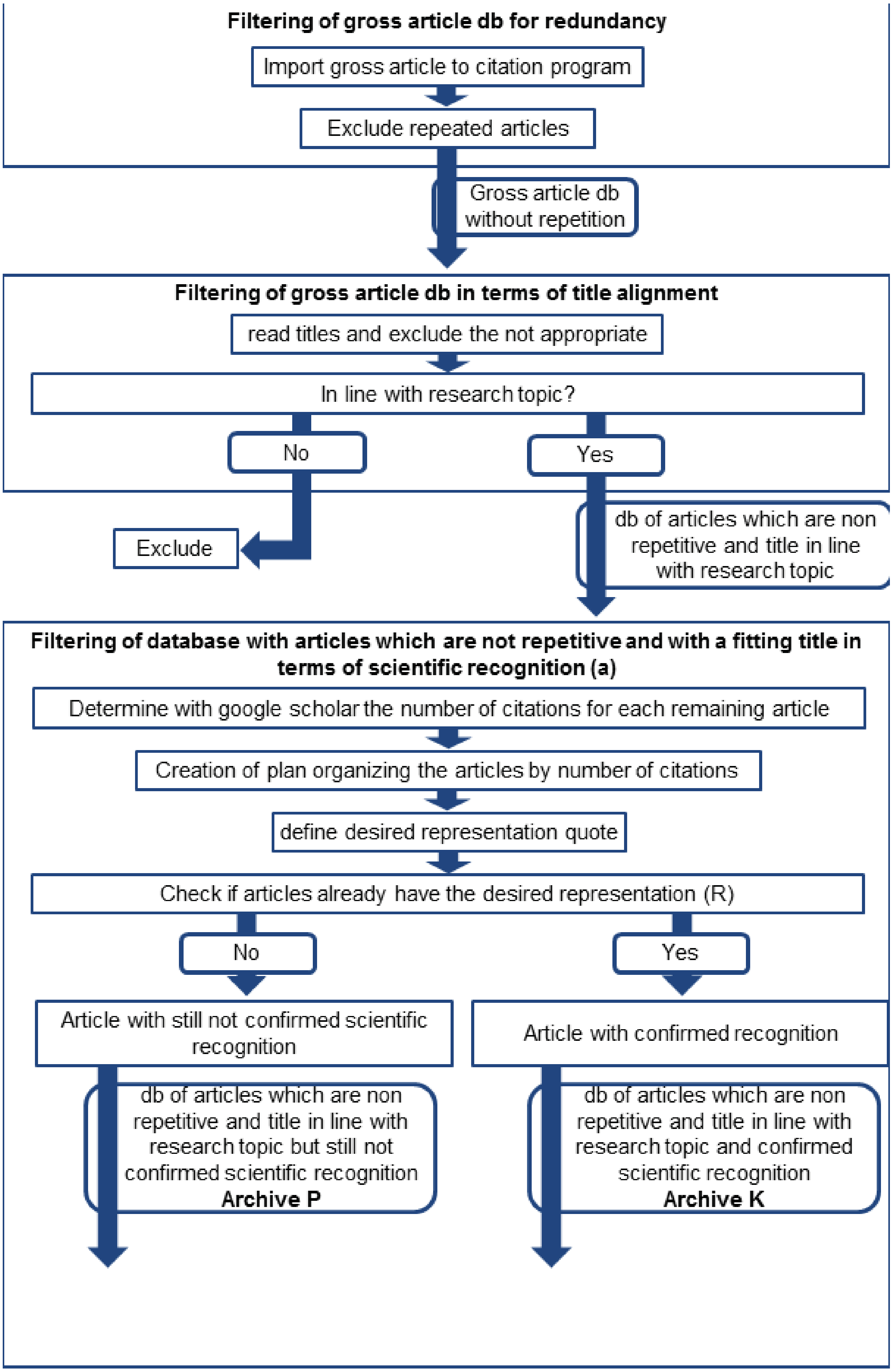
Transmission upgrades due to solar
Transmission upgrades due to wind
Electric Bill Management
Grid-Connected Commercial (Reliability & Quality)
Grid-Connected Residential (Reliability)
Frequency Regulation
Transportable Transmission/Distribution Upgrade Deferral
Stationary Transmission/Distribution Upgrade Deferral
Onsite Renewable Generation Shifting
Electric Bill Management with Renewables
Renewables Energy Time Shift
On-Site Power
Transportation Services
Microgrid Capability
Resiliency
Demand Response

SOURCE: Sandia national laboratories (2016)

Annex 2

ANNEX 2: COMPLETE LITERATURE ANALYSIS PROCESS




Filtering of gross article db for redundancy
Import gross article to citation program
Exclude repeated articles
Gross article db without repetition
Filtering of gross article db in terms of title alignment
read titles and exclude the not appropriate
In line with research topic?
No
Yes
Exclude
db of articles which are non repetitive and title in line with research topic
Filtering of database with articles which are not repetitive and with a fitting title in terms of scientific recognition (a)
Determine with google scholar the number of citations for each remaining article
Creation of plan organizing the articles by number of citations
define desired representation quote
Check if articles already have the desired representation (R)
No
Yes
Article with still not confirmed scientific recognition
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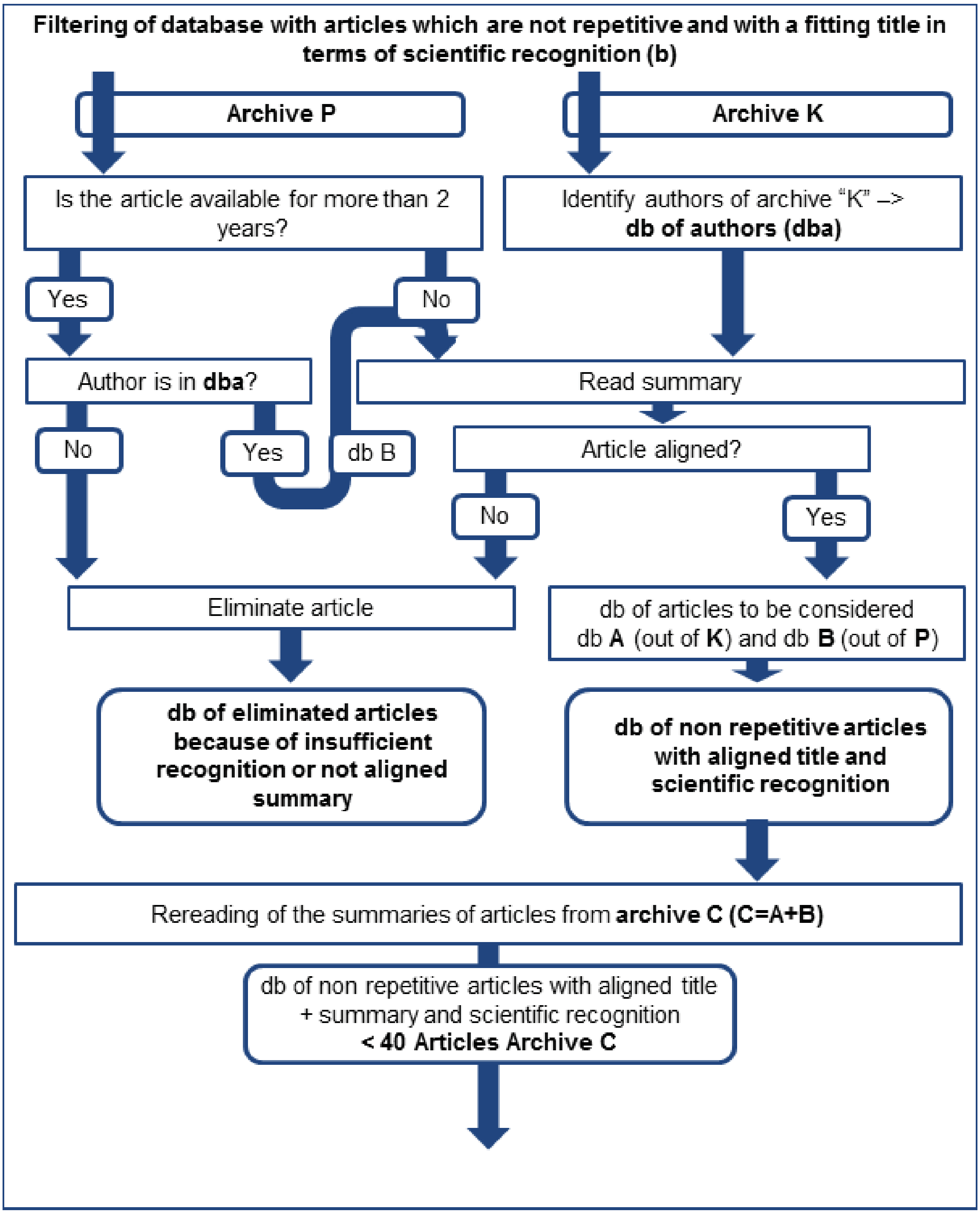
Archive P
db of articles which are non repetitive and title in line with research topic and confirmed scientific recognition
Archive K



SOURCE: ENSSLIN, L., ENSSLIN, S. R., LACERDA, R. T. O. & TASCA, J. E. Processo de Seleção de Portfólio Bibliográfico. Processo técnico com patente de registro pendente junto ao INPI. Brasil 2010.