Investment planning for flexibility sources and transmission lines in the presence of renewable generation

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DOCTORAL THESIS

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Investment planning for flexibility sources and transmission lines in the presence of renewable generation

Dina Khastieva

Investment planning for flexibility sources and transmission lines in the presence of renewable generation

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Dissertation

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Monday 07 September 2020 at 13:00 o'clock

by

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The doctoral research has been carried out in the context of an agreement on joint doctoral supervision between Comillas Pontifical University, Madrid, Spain, KTH Royal Institute of Technology, Stockholm, Sweden and Delft University of Technology, the Netherlands.

Keywords: energy storage, wind generation, regulation, incentive mechanism, transmission, investment planning, coordinated investments, decomposition techniques, Benders decomposition, large scale optimization, disjunctive programming

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Contents

Summary (English)

Samenvatting

- Title: Investment planning for flexibility sources and transmission lines in the presence of renewable generation
- Language: English
- Author: Dina Khastieva
- Division of Electric Power and Energy Systems, EECS school, KTH Royal Institute of Technology

Environmental and political factors determine long-term development for renewable generation around the world. The rapid growth of renewable generation requires timely changes in power systems operation planning, investments in additional flexible assets and transmission capacity.

The development trends of restructured power systems suggest that the current tools and methodologies used for investment planning are lacking the coordination between transmission and flexibility sources. Moreover, a comprehensive analysis is required for efficient investment decisions in new flexibility sources or transmission assets. However, literature does not provide an efficient modeling tool that will allow such a comprehensive analysis.

This dissertation proposes mathematical modeling tools as well as solution methodologies to support efficient and coordinated investment planning in power systems with renewable generation. The mathematical formulations can be characterised as large scale, stochastic, disjunctive, nonlinear optimization problems. Corresponding solution methodologies are based on combination of linearization and reformulation techniques as well as tailored decomposition algorithms. Proposed mathematical tools and solution methodologies are then used to provide an analysis of transmission investment planning, energy storage investments planning as well as coordinated investment planning. The analysis shows that to achieve socially optimal outcome

transmission investments should be regulated. Also, the results of the simulations show that coordinated investment planning of transmission, energy storage and renewable generation will result in much higher investments in renewable generation as well as more efficient operation of renewable generation plants. Consequently, coordinated investment planning with regulated transmission investments results in the highest social welfare outcome.

Summary (Swedish)

Sammanfattning

- Title: Investment planning for flexibility sources and transmission lines in the presence of renewable generation
- Language: Swedish
- Author: Dina Khastieva
- Division of Electric Power and Energy Systems, EECS school, KTH Royal Institute of Technology

Miljöfrågor och politiska faktorer styr den långsiktiga utvecklingen för förnybar elproduktion runtom i världen. Den snabba ökningen av förnybar elproduktin kräver att drift och planering av elsystem ändras i god tid, investeringar i ytterligare flexibla resurser och ytterligare transmissionskapacitet.

Utvecklingstrenderna för omstrukturerade elsystem antyder att de nuvarande verktygen och metoderna för investeringsplanering saknar koordinering mellan transmission och flexibla resurser. Dessutom krävs en omfattande analys för investeringsbeslut i flexibla resurser eller transmissionssystem. Det finns dock inte i litteraturen en effektiv modell som möljliggör en sådan omfattande analys.

Den här avhandlingen föreslår matematiska modelleringsverktyg såväl som lösningsmetoder för att stödja effektiv och koordinerad investeringsplanering i elsystem med förnybar elproduktion. De föreslagna matematiska verktygen och lösningsmetoderna används sedan för att tillhandahålla en analys av investeringsplanering för transmissionssystem respektive energilager samt koordinerad investeringsplanering. De matematiska modellerna kan beskrivas som storskaliga, stokastiska, disjunktiva, icke-linjära optimseringsproblem. Lösningsmetoderna för dessa problem är baserade på en kombination av linjärisering och omformulering samt skräddarsydda dekomponeringsalgoritmer. Analysen visar att för att uppnå maximal samhällsnytta bör investeringar in transmissionssystem vara reglerad. Dessutom visar resultaten

från simuleringarna att koordinerad investeringsplanering för transmission, energilager och förnybar elproduktion kommer att resultera i större investeringar i förnybar elproduktion samt ett mer effektivt utnyttjande av de förnybara kraftverken. Följdaktligen resulterar koordinerad investeringsplanering med reglerade investeringar i transmission ger det bästa utfallet ur samhällsekonomisk synvinkel.

Summary (Dutch)

Samenvatting

- Title: Investment planning for flexibility sources and transmission lines in the presence of renewable generation
- Language: Dutch
- Author: Dina Khastieva
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Ecologische en politieke factoren bepalen de lange termijn planning voor duurzame elektriciteitsproductie over de hele wereld. De snelle groei van hernieuwbare productie vereist tijdige veranderingen in de operationele planning van energiesystemen, investeringen in aanvullende ondersteunende flexibele centrales en extra transmissiecapaciteit.

De ontwikkelingstrends van geherstructureerde energiesystemen suggereren dat de huidige tools en methodologieën die worden gebruikt voor investeringsplanning, de coördinatie tussen transmissie- en flexibiliteitsbronnen missen. Bovendien is een uitgebreide analyse vereist voor efficiënte investeringsbeslissingen in nieuwe flexibiliteitsbronnen of transmissiecapaciteit. De literatuur voorziet echter nog niet in een efficiënte modelleertool voor een dergelijke samenhangende analyse.

Dit proefschrift presenteert wiskundige modelleertools voor, evenals oplossingsmethoden ter ondersteuning van efficiënte en gecoördineerde investeringsplanning in energiesystemen met hernieuwbare opwekking. De mathematische modelleeruitdaging kan gekarakteriseerd worden als het oplossen van grootschalige, stochastische, disjuncte, nonlineaire optimalisatieproblemen. Uit de analyse blijkt dat transmissie-investeringen gereguleerd moeten worden om een welvaartsoptimaal resultaat te bereiken. Ook laten de resultaten van de numerieke simulaties zien dat een gecoördineerde investeringsplanning voor transmissie, energieopslag en hernieuwbare opwekking zal

leiden tot veel hogere investeringen in hernieuwbare opwekking en in een efficiëntere exploitatie van installaties voor hernieuwbare opwekking. Bijgevolg resulteert gecoördineerde investeringsplanning met gereguleerde transmissie-investeringen in de hoogste welvaartsuitkomst.

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Finally, and most importantly, I want to thank my family: my mom Nailia for her support, motivation and pushing me to work more (sometimes to the edge) and never give up; my aunts Rizida and Fanya, uncle Rinat, my cousins and all other relatives for wishing the best for me and their prayers. Without you, I would have not achieved anything.

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List of Symbols

a_{etks}	Energy storage charge/discharge indicator;
z_{mt},y_{mt}	Transmission investment decision variables;
$I_n^{(d)}$	Incidence matrix element of load d, node n;
$J_n^{(g)}$	Incidence matrix element of generator g, node n;
$R_n^{(l)}$	Incidence matrix element of receiving node n, line l;
$\overline{R}_n^{(m)}$	Incidence matrix element of receiving node n, line m;
$S_n^{(l)}$	Incidence matrix element of sending node n, line l;
$\overline{S}_n^{(m)}$	Incidence matrix element of sending node n, line m;
$W_n^{(w)}$	Incidence matrix element of generator w, node n;
A_d	Load d marginal utility;
$C_e^{(ch)}$	Cycling cost of charging energy storage unit e;
$C_e^{(dh)}$	Cycling cost of discharging energy storage unit e;
$C_{et}^{(E)}$	Investment cost of energy storage energy capacity for candidate unit e at period t;
C_g	Marginal cost of generator unit g;
$C_{et}^{(P)}$	Investment cost of energy storage power capacity for candidate unit e at period t;
$C_{mt}^{(T)}$	Investment cost of transmission line m at period t;

$C_{wt}^{(W)}$	Investment cost of renewable unit w at period t;
D_d	Maximum capacity of load d at period t;
F_l	Maximum capacity of existing transmission line l;
$\widehat{F}_m$	Maximum capacity of candidate transmission line m;
G_g	Maximum capacity of generator g;
$\widehat{G}_w$	Maximum capacity of renewable generator w;
π_s	Probability of scenario s;
Ψ	Number of operational periods in an investment period;
i_t	Interest rate;
Θ	Maximum voltage angle;
ϱ_{wtks}	Stochastic output of renewable generator w at period t, k, scenario s;
Ξ_m, Ξ	Sufficiently large constants;
X_l	Reactance of existing transmission line l;
X_m	Reactance of candidate transmission line m;
$\underline{\vartheta}_{etks}$	Lagrange multiplier for constraint (4.15c)
$\overline{\vartheta}_{etks}$	Lagrange multiplier for constraint (4.15c)
$\underline{\omega}_{dtks}$	Lagrange multiplier for constraint (4.2p)
$\overline{\omega}_{dtks}$	Lagrange multiplier for constraint (4.2p)
$\underline{\kappa}_{etks}$	Lagrange multiplier for constraint (4.15b)
$\overline{\kappa}_{etks}$	Lagrange multiplier for constraint (4.15b)
σ_{ltks}	Lagrange multiplier for constraint (4.2d)
$\underline{\sigma}_{ltks}$	Lagrange multiplier for constraint (4.2g)
$\overline{\sigma}_{ltks}$	Lagrange multiplier for constraint (4.2g)
$\underline{\nu}_{gtks}$	Lagrange multiplier for constraint (4.2k)
$\overline{\nu}_{gtks}$	Lagrange multiplier for constraint (4.2k)
$\overline{\vartheta}_{htks}$	Lagrange multiplier for constraint (4.2h)
$\underline{\vartheta}_{htks}$	Lagrange multiplier for constraint (4.2h)

$\underline{\rho}_{htks}$	Lagrange multiplier for constraint (4.2j)
ϑ_{et}	Lagrange multiplier for constraint (4.16b)
κ_{et}	Lagrange multiplier for constraint (4.16a)
η_{wt}	Lagrange multiplier for constraint (4.16c)
$\underline{\varrho}_{mtks}$	Lagrange multiplier for constraint (4.19b)
$\underline{\xi}_{mtks}$	Lagrange multiplier for constraint (4.19c)
$\overline{\xi}_{mtks}$	Lagrange multiplier for constraint (4.19c)
$\overline{\varrho}_{mtks}$	Lagrange multiplier for constraint (4.19a)
$\underline{\gamma}_{mtks}$	Lagrange multiplier for constraint (4.10)
$\overline{\gamma}_{mtks}$	Lagrange multiplier for constraint (4.10)
τ_{etks}	Lagrange multiplier for constraint (4.2e)
$\underline{\rho}_{etks}$	Lagrange multiplier for constraint (4.15d)
θ_{htks}	Lagrange multiplier for constraint (4.2f)
$\overline{\theta}_{htks}$	Lagrange multiplier for constraint (4.2i)
$\underline{\theta}_{htks}$	Lagrange multiplier for constraint (4.2i)
$\overline{\rho}_{etks}$	Lagrange multiplier for constraint (4.15d)
$\lambda 0_{ntks}$	Lagrange multiplier for constraint (4.2q)
$\underline{\kappa}_{ftks}$	Lagrange multiplier for constraint (4.15a)
$\overline{\kappa}_{ftks}$	Lagrange multiplier for constraint (4.15a)
λ_{nts}	Lagrange multiplier for constraint (4.2b)
$e \in \mathcal{E}$	Set of energy storages;
$d \in \mathcal{D}$	Set of loads;
$g \in \mathcal{G}$	Set of generators;
$k \in \mathcal{K}$	Set of operation periods;
$l \in \mathcal{L}$	Set of existing lines;
$m \in \mathcal{M}$	Set of candidate lines;
$n \in \mathcal{N}$	Set of nodes;

$h \in \mathcal{H}$	Set of hydro generators;
$s \in \mathcal{S}$	Set of scenarios;
$t \in \mathcal{T}$	Set of investment periods;
$w \in \mathcal{W}$	Set of renewable-energy generators;
$\tilde{d}_{etks}$	Charge of energy storage e at period t, k, scenario s;
d_{dtks}	Demand of load d at period t, k, scenario s;
e_{et}	Energy capacity of energy storage e at period t;
f_{ltks}	Flow of line l at period t, k, scenario s;
$\widehat{f}_{mtks}$	Flow of line m at period t, k,scenario s;
$\tilde{g}_{etks}$	Discharge of energy e at period t, k, scenario s;
g_{gtks}	Generation of generator g at period t, k, scenario s;
$\overline{g}_{htks}$	Generation of generator h at period t, k, scenario s;
u_{htks}	Inflow of generator h at period t, k, scenario s;
m_{ht-1ks}	Reservoir level of generator h at period t, k, scenario s;
s_{htks}	Spillage of generator h at period t, k, scenario s;
$\widehat{g}_{wtks}$	Renewable output of unit w at period t, k, scenario s;
p_{et}	Power capacity of energy storage e at period t;
Φ_t	Fixed fee at period t;
q_{etks}	State of charge of energy e at period t, k, scenario s;
θ_{ntks}	Voltage angle at node n at period t, k, scenario s;
u_{wt}	Investment level in renewable generator w at period t;

List of Acronyms

ESS	Energy Storage Systems
BSS	Battery Storage Systems
ISS	Incremental Subsidy Surplus
TSO	Transmission System Operator
ISO	Independent System Operator
SO	System Operator
MO	Market operator
KKT	Karush-Kuhn-Tucker
H-R-G-V	Hesamzadeh-Rosellon-Gabriel-Vogelsang mechanism
H-R-V	Hogan-Rosellon-Vogelsang
MPEC	Mathematical program with equilibrium constraints
LP	Linear problem
MILP	Mixed-integer linear problem
MINLP	Mixed-integer nonlinear problem
NLPEC	Nonlinear disjunctive program with equilibrium constraints
CAES	Compressed air energy storage
JCR	Journal Citation Report
RES	Renewable Energy Sources
NRECA	National Rural Electric Cooperative Association
EENS	Expected Energy Not Served
LOLP	Lost of load probability

Chapter 1

Introduction

Power systems face continuous transition; demand levels are continuously changing; infrastructure is aging, new regulation is being adopted each year; new technologies are developing; prices of fuels and material as well as capital costs of technologies are changing. All these changes and transformations are highly uncertain and, as a result, create challenges for investment planning in the power sector. For example, transmission infrastructure development highly depends on regulation and changing needs of the power system while integration of energy storage technologies depends not only on changing flexibility and storage needs but equally on technology and material development. Investment planning in power systems is especially complicated because it involves decision making in large and expensive assets with long construction time. More importantly, successful investments require a reliable long-term outlook on power system development. A long-term outlook consists of various assumptions and forecasts with respect to fuel prices, market and regulatory changes as well as development of new technologies and their costs. All power system development assumptions are highly interdependent and form a complex multisector and multidisciplinary system. In order to create a reliable long-term outlook, ideally, a comprehensive stochastic simulation tool of the power sector would be required. However, given the current state of operational research tools and computational capability, this is not possible. Therefore, it is important to simplify the system by fixing a set of assumptions based on expert opinion and adapting simulation tools with simplified models of the power system sector. The simplifications are especially relevant for power systems with large scale renewable generation due to uncertainty connected to short-term renewable generation as well as uncertainty connected to technological developments (i.e., energy storage technologies and transmission network) to support the intermittent nature of renewable generation. As a result, an important question arises; "which parameters can be treated as external assumptions and which should be treated as variables in the investment planning of an asset?". Moreover, another important question is, "to which extent should an investment planning problem be simplified without losing reliability of the result?". This dissertation implicitly addresses the aforementioned questions and provides modeling and solution methodologies for investment planning while considering the multisector and multidisciplinary characteristics of the power sector.

This chapter introduces the literature gap and research objectives of this dissertation. The chapter begins with a short introduction into investment planning in Section 1.1. Section 1.2 provides the motivation and identifies the knowledge gap on investment planning in systems with large scale renewable generation penetration. Motivated by the identified literature gap, Section 1.3 states the research objectives of this thesis as well as proposed methodologies to achieve these objectives. The list of publications is presented in Section 1.4 followed by Section 1.5 where the main contributions and conclusions of this dissertation are summarized. Finally, Section 1.6 presents the outline for the remaining chapters.

1.1 Background

Initially, the first power systems evolved as natural monopolies. The technically complicated operational structure of a power system was not able to accommodate market based interaction between generators, transmission and demand while at the same time guaranteeing constant and reliable supply of electricity. However, with the developments in telecommunication, operational research and economic theory, the transition to market based operation became possible. The transition began with the development of electricity markets where loads, generators and other eligible parties buy or sell electricity. The generation and demand sectors of the majority of European and American power systems were successfully liberalized and nowadays can be operated through competitive market rules. On the other hand, transmission infrastructure still remains a natural monopoly and relies on various subsidies and other incentives from a governing entity (which is the case in USA) or very high transmission fees and grid tariffs allocated to loads (which is the case in Sweden). Nowadays, the most common power system governance structure consists of an independent profit maximizing load, energy storage and generation utilities, an independent transmission company (profit maximizing or state owned), a regulatory entity, and a market operator and can be illustrated as in Figure 1.1.

In Figure 1.1, the bottom layer illustrates customers of the power grid which consists of loads, generation and energy storage utilities. Nowadays, pure energy storage utilities are quite rare and energy storage technologies are more commonly owned and operated by a generation or load utility. However, the expected growth of energy storage projects makes it likely to expect a higher share of pure energy storage utilities. Load utilities include large loads and retail companies. The mid-layer consists of entities which are responsible for operation and planning in power systems. Market Operator illustrates a centralized entity responsible for operation and market clearance in a power system while Transmission Company is used to illustrate a centralized entity responsible for operation and planning of power flows

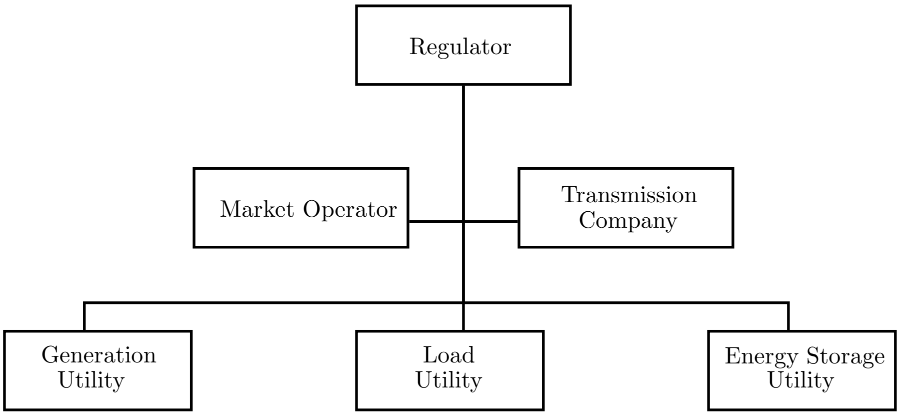

Figure 1.1: Power system governance structure

between nodes and investments and maintenance of transmission assets. The upper layer (Regulator) illustrates any centralized entity which is responsible for any incentives and other regulatory measures required in a power system.

The transition from vertically integrated to horizontally integrated economy in power systems is accompanied by the increasing concern about climate change and, as a result, the change in the desirable generation mix. The worldwide view on the future generation mix is consolidated under the idea that carbon dioxide (CO_2) emitting power plants should be reduced to a minimum number or eliminated entirely. The projected growth of electricity demand around the world not only does not allow to simply close CO_2 emitting power plants but requires an efficient and fossil free generation alternative. Renewable and CO_2 neutral generation such as wind and solar is seen as one of the promising alternatives to replace CO_2 emitting power plants.

The renewable energy industry is growing rapidly around the world. The development of new technologies and various environmental and political factors are gradually making renewable generation desirable and affordable. Threats of global climate change followed by carbon dioxide emission reduction targets force governments around the world to provide additional incentives for renewable generation investments, e.g., through subsidies, green certificates, etc. According to the International Energy Agency, wind based generation capacity alone will cover 18% of the world's electricity consumption by 2050. At the same time numerous European countries such as Germany, Sweden, France and Belgium have an ambition to reach 100% CO_2 free electricity generation by 2050. Policy driven generation investments resulted in a large number of wind farm installations around Europe, China and USA just over the last decade [1]. Moreover, policies and governmental support allowed renewable technology to reach a mature state in a short period of time. Appropriately designed incentive mechanisms resulted in large scale integration of renewable generation capacity, development of more efficient technologies, as well as reduced capital and operational costs of renewable generation. However, the surrounding system development including flexibility assets and transmission infrastructure develops at a much slower rate. The slower rate of development can be connected to lack of price signals and incentive mechanisms. As a result not all benefits and available capacities of renewable generation are fully utilized. For example, a wind investment project will not take place unless necessary transmission infrastructure is in place or under development. If a wind generation project will precede transmission expansion then the wind generation project owner will not be able to operate and sell energy while waiting for transmission project to be built. Thus, the wind generation project owner will lose income due to the decreased operational lifetime of the project. At the same time transmission investments and grid reinforcements will not take place unless there is an existing need (generation or load already in place). Moreover, delayed development of flexibility assets and transmission may result in operation disturbances of a power system with high shares of renewable generation.

Small and geographically well distributed wind installations do not usually induce alarming disturbances to power systems. However, a large amount of wind based generation at one location could be a potential problem for power system security. Variability and unpredictability of large wind farms may require better balancing of the power grid such as improved frequency control and larger reserve capacities [2]. The balancing need of power systems with large wind generation penetration has been studied in [3],[4] and [5] and in more recent publications such as [6],[7],[8] and [9].

In addition, the literature suggests that available transmission capacities will not be sufficient to accommodate large shares of renewable generation and, as a consequence, additional transmission investments may be required [10]. Moreover, due to the natural monopoly of transmission infrastructure, such investments cannot be guaranteed with competitive markets rules. Therefore additional regulatory mechanisms should be in place [11].

The challenges posed by large wind based generation installation can be divided into three main types:

- *Uncertainty* related to limited predictability of wind speed. Increased uncertainty in operation and planning of power systems will require large reserve capacity and additional flexibility sources such as energy storage with fast ramping capability.

- *Variability* of the wind speed. Similar to uncertainty, increased variability may require improvements in ramping capability of power systems. The variability of the wind speed is especially important for large scale wind farms. Wind power production can change rapidly over a short period of time. Thus, in combination with approximately uniform wind speed throughout a small geographic area, a small change in wind speed may cause a drastic change in power output.

- *Geographical distribution* of large scale wind farms. Wind generation output is dependent on wind speed. Oftentimes, the windy and attractive areas for wind installations are poorly connected to the power grid. Thus, additional transmission infrastructure or reinforcements of transmission infrastructure are necessary.

The main investment problems in power systems with high shares of renewable generation can be divided into two main areas: investments in flexibility sources and investment in transmission infrastructure.

1.1.1 Investment planning process

Every utility in the power sector adopts its own investment planning procedures. While the details of the procedures may vary, the overall process has major similarities and follows the same steps. The steps of the investment planning can be described as:

- First, potential feasible technologies are identified and monitored.
- Second, major assumptions on market structures of the future and regulation are made
- Third, a long-term power system outlook is performed using mathematical models. The outcome of such long-term outlook is usually capacity developments of selected technologies and long-term price curves of selected electricity markets.
- Fourth, based on the long-term power system outlook, individual investment decisions are evaluated and taken.

For instance, consider a utility which wants to invest in an energy storage project. In order to calculate profitability and risks, the utility would need to to use long-term price curves under different market development scenarios. Additionally, in order to forecast long-term price curves a utility needs to have an outlook on the development of the power system as a whole. This outlook is usually created by simulating the development of the power system and including all monitored technologies which were selected as the most promising, meaning an optimization investment model should be developed where investment in various assets are performed simultaneously. Once an outlook is finalized, price curves are developed and the profitability and risks are estimated, a utility can take an informed decision on energy storage investment. The investment process is illustrated in 1.2.

Table 1.1 provides a summary of the main technologies currently considered in

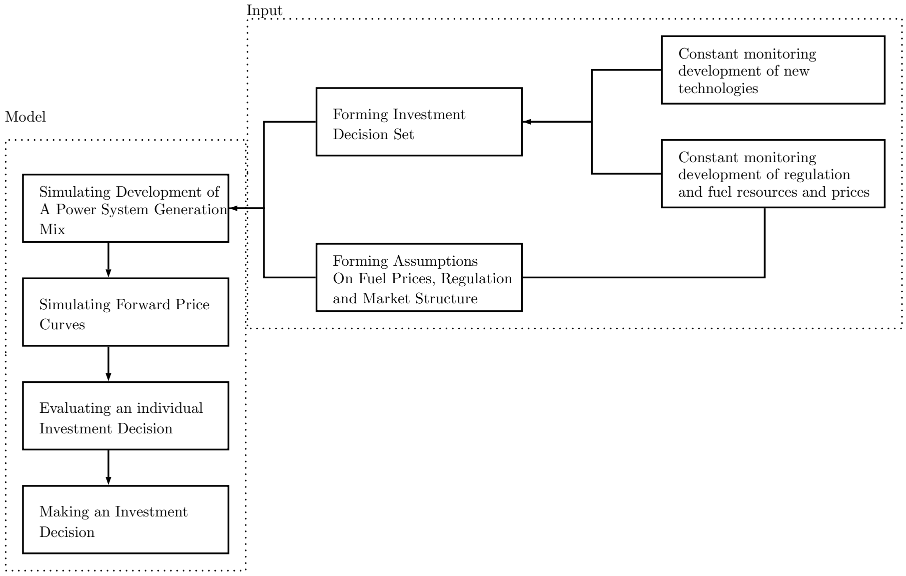

Figure 1.2: Investment planning process

the future power system planning in the majority of utilities to accommodate high shares of renewable generation.

Group	Technologies	Description
Baseload Technologies	CCGT Hydro power	Large scale generators with fast response and good ramping rate
Peaking power	Diesel generators OCGT	Small scale generators with fast response and fast start up
Demand response	Background processes Manufacturing processes Aggregated loads	Large scale industrial or aggregated small scale loads
Energy Storage	Lithium-ion batteries Pumped Storage	Scalable Energy storage assets which can be used for various applications
Transmission	Reinforced New transmission links	Controllable large scale transmission links

Table 1.1: Technologies considered for the future development of the power sector

Most of the literature addresses the investment planning in the technologies listed in Table 1.1 separately and under fixed long-term outlook. Generally, the literature which covers coordinated investment planning both in flexibility sources and transmission infrastructure is very limited. Literature reviews on flexibility sources and transmission infrastructure are presented in Section 1.1.2 and in Section 1.1.3 respectively. These sections also include literature where coordinated investment planning was taken into account but the main focus was flexibility sources or transmission infrastructure.

1.1.2 Literature review on operation and planning of flexibility sources

Investments in flexible generation technologies such as gas turbines were addressed in [12] and [13]. Thermal generation investments have been studied in-depth and do not contain a large literature gap. At the same time, investments in hydro power plants are complicated due to geographical and location restrictions. On the other hand, energy storage technologies are considered to be the most popular source of flexibility which can be potentially integrated in the transmission system and support further development of large scale wind based generation. Various references provide an overview on possible applications and assessment of energy storage benefits. In [14], a comprehensive analysis of possible energy storage applications and suitable energy storage technologies are presented. Applications may vary from energy arbitrage to grid upgrade investment deferral. The most promising applications for energy storage include energy arbitrage, balancing services and renewable generation support. Different ways how energy storage systems can be used for balancing applications, especially in the presence of a large amount of variable renewable generation, were studied in [15] and in [16], while [17] includes benefits of energy storage as a flexibility source. In addition, [18] and [19] analyze how energy storage can be beneficial for supporting variable wind power generation and [20] presents benefits of energy storage from a technical point of view and its effect on maximum wind power penetration. A review of modeling techniques of energy storage given different objectives is provided in [21] and includes more than 150 papers on the energy storage assessment subject. The literature provides evidence that energy storage is beneficial for renewable generation support and can be profitable under certain assumptions, however, high capital cost is seen as the main obstacle in energy storage market development. Cost evaluation and calculation of different energy storage technologies is presented in [22] and [23].

The aforementioned papers have shown that additional capacity of flexibility sources such as energy storage will be required to reach future renewable targets. Also literature suggests that energy storage might be profitable in systems with a high share of renewables. However, the financial profitability of the energy storage is still strongly dependent on the size and location of the deployed energy storage system. Optimal planning of energy storage under different conditions and objectives has been studied in [18],[24],[25],[26],[27],[28],[29] and [30]. In addition,

[31],[32],[33],[34],[35] investigated joint optimal allocation and sizing of energy storage. In [36], the authors also show that energy storage is beneficial for renewable generation expansion and that joint optimization of renewable generation and flexibility sources including energy storage results in much higher cost savings than when investment planning is performed separately. However, these papers consider centralized investment planning which does not ensure profitability of the energy storage system itself and does not consider profit maximizing behavior of the energy storage investor. It is an open question whether flexibility sources such as energy storage should be a market asset or system asset. Under current European regulation energy storage cannot be used to obtain profit if it is owned by system operators. Thus, the current development of energy storage will mostly depend on various independent investors (e.g., generation utility, energy storage utility) which have profit maximizing objectives and other constraints on expected profit. A profit maximizing bilevel approach for investment planning of energy storage systems which will ensure that the owner of the energy storage will maximize its benefits has been proposed in [37],[38] and [31]. In [39] a bilevel approach is used to simulate merchant energy storage while accounting for optimal bidding strategy. However, neither of the proposed models includes other sources of flexibility such as hydro power and flexible demand which are currently the main competitors of emerging energy storage systems. Moreover, these models do not take into account possible growth of renewable generation or development of transmission infrastructure. These research gaps were addressed in publications $J1$,$J2$ and $J4$ (see Section 1.4) and is used to formulate the general contribution points of this dissertation $C1$, and $C3$-$C5$ (see Section 1.5).

1.1.3 Literature review on incentive based transmission investments

Liberalization of electricity markets decoupled operation and planning of major players of power system's markets (e.g., generation, demand, energy storage, transmission) with the aim of increasing competition and increasing the security of supply. For consumers of electricity markets (e.g., generation, demand and energy storage) the transition from centralized power market to competitive markets was successful regardless of various challenges and milestones. On the other hand, the full transition from a centralized operation and planning to competitive market-based operation and planning did not take place in the transmission sector. In the majority of states, the transmission sector transitioned to a natural monopoly or oligopoly. Due to the vital importance of transmission infrastructure for security of supply and functioning of any power system, transmission operation and planning are highly regulated. The regulation aims to achieve social welfare maximum operation and planning of transmission infrastructure.

The transmission operation and planning were addressed in various references. In [40] and [27] transmission investment planning is studied accounting for uncertainties (e.g., uncertainties from renewable generation). However, the majority of the literature, including the aforementioned, does not consider the existing regulation or market influence and assumes perfect information exchange between all actors of a power system. In [41] and [42], the authors propose market-based transmission expansion planning under uncertainty formulated through bilevel mixed-integer MPEC models. In [43], a three-level model is proposed for market-based transmission and generation expansion. Publications [44] and [45] propose mathematical models for coordination of strategic generation investments and transmission investments. In [46], a game-theoretical approach is used for the operation and planning of a transmission company in coordination with strategic generators. The presented methods prove that the market based approach can be efficient in the transmission planning. However, these papers do not include regulation or incentive mechanisms which can be used to ensure socially optimal investment planning.

The incentive problem for the transmission expansion planning has been addressed elsewhere in relevant literature: Physical characteristics of electricity (such as loop flows), economies of scale, and dynamics between the forward transmission market and other markets are mentioned as complicating factors in the analysis of incentives for the transmission expansion planning [47], [48]. Various incentive mechanisms were proposed to tackle the incentive problem. They can be divided into two major groups; subsidy mechanisms and constraint mechanisms. Subsidy mechanisms were initially introduced by [49] and further developed by [50] where an incremental surplus subsidy scheme (ISS) was proposed. The mechanism then was applied to transmission pricing and investments in [51]. On the other hand, constraint mechanisms were proposed in [52] and [53], where price-cap constraints were proposed for incentivizing transmission expansion planning by a transmission company. Under certain conditions, these mechanisms lead to a transmission expansion plan which maximizes social welfare [54]. Reference [55] proposes a reward/penalty mechanism. In this mechanism, the regulator rewards the Transco when the transmission network is expanded and the congestion rents are decreased. Reference [56] proposes an out-turn mechanism. The out-turn is defined as the difference between actual electricity prices and prices without transmission congestion. The Transco is responsible for total out-turn cost and any transmission losses. References [54] and [57] extend the work in [52] and propose the H-R-V (Hogan-Rosellon-Vogelsang) mechanism for transmission expansion planning. In the H-R-V mechanism, the Transco maximizes its profit (sum of merchandising surplus and a fixed fee minus transmission investment costs) subject to the price-cap constraint introduced in [52]. The H-R-V mechanism has been numerically tested in simplified models of Northwestern Europe and the Northeast U.S. [54], [58]. Mathematically, the H-R-V model is a nonlinear disjunctive program with equilibrium constraints (NLPEC). Local optimizers have been used to solve the corresponding model but with no guarantee of global optimality. Moreover, complex algorithms used to solve such problems have a high computation time and they are hardly applicable to large scale problems with many decision variables. More recently, an alternative incentive mechanism for transmission expansion planning is proposed in [11] following the incentive mechanisms in [50] and [54]. The H-R-G-V (Hesamzadeh-

Rosellon-Gabriel-Vogelsang) mechanism proposes a dynamic interaction between a profit-maximizing Transco, the regulator and an Independent System Operator (ISO).

In [11] the authors prove in analytic models that the H-R-G-V mechanism will lead to the socially maximum investment planning decisions. However, the direct application of the mechanism to the transmission planning will lead to a bilevel nonlinear disjunctive program with equilibrium constraints. As it was mentioned before, it is hard to guarantee the convergence to the globally optimal solution of such type of problems. As a result, finding an optimal incentive mechanism for transmission expansion planning is an open question both in theory and in practice. This research gap is addressed in the publication $J2 - J4$ (see Section 1.4) and is used to formulate a general contribution points of this dissertation $C2$-$C5$ (see Section 1.5).

1.2 Research objectives

Based on the above literature review and identified literature gaps in Section 1.1.2 and Section 1.1.3, the following research objectives can be summarized:

- Mathematical models used for investment decisions should consider long-term development of the power sector, as well as financial markets in the life-time of the asset under consideration. Thus, the first objective of this thesis is to understand key driving factors of the investment in flexibility sources and transmission assets as well as to identify sources of uncertainty which might increase the risks of the investment into transmission lines and energy storage systems.

- Various incentive regulations can be used to stimulate investments into transmission lines or flexibility assets. Various economic theories were proposed in the literature in order to address the investment incentive problem. However, a comprehensive analysis is needed to derive the optimal incentive policy for transmission and energy storage to accommodate the growth of renewable energy. Thus, the second objective of this thesis is to select the most promising incentive mechanism which will provide the most socially beneficial investments.

- In order to include all identified drivers and sources of uncertainty, a comprehensive mathematical model is required to find the optimal values and allocation of transmission and energy storage investments. Moreover, the formulation of such comprehensive models should be as efficient as possible and avoid unnecessary constraints and variables. Thus, the third objective of this thesis is to provide concise but comprehensive mathematical model formulations for transmission and energy storage investment planning problems.

- Comprehensive models are usually large and often nonlinear. This is also the case with the majority of transmission and energy storage investment models. A solution methodology is needed in order to address the challenges of the proposed models and improve computational tractability. Thus, the final objective of this thesis is to provide a generalized solution methodology applicable to a wide class of investment planning problems including transmission and energy storage investment models.

1.3 Methodology

Investment planning in power systems is complicated due to unique characteristics of the system. The decisions should be taken not only considering financial aspects, but also however including technical and regulatory constraints applied to the whole system under consideration.

The main aim of any investment planning is to discover an investment decision and an appropriate time for investment which will lead to the maximum difference between expected benefits in the future and the investments costs. The driving forces for investment planning in power systems can be classified into two groups: driving forces of an independent investor who owns the assets and driving forces of the system as an independent agent itself. From the independent owner point of view these driving forces are straightforward and can be fit into a few points:

- Revenue generation
- Risk minimization
- Back-up for other existing assets in the portfolio
- Advanced replacement of aged assets
- Adaptation to regulatory measures

The system goals, on the other hand, differ from purely technical to socially oriented goals. System goals include:

- Improvement of reliability of the system
- Improvement of delivery and quality
- Social benefits
- Environmental concerns
- Anticipated future needs

Any investment decision involves certain levels of risks. Risks can be associated with various long term or short term uncertainty. Long term risks are consequences of long term uncertainty such as investment costs, new technology development and regulation while short term risks are associated with operational uncertainty such as outages, electricity and fuel prices and wind generation forecast errors. Risks are subjective factors. However, they can be quantified and analyzed. Risks appear when any kind of uncertainty is involved. Prediction and forecast tools are used to simulate uncertainty and estimate risks.

In general, any intuitive methodology used to facilitate investment planning in power system includes three major steps:

- Identification of uncertainty and scenario generation for corresponding uncertainty
- Simulation of the decision making which includes mathematical modeling and optimization
- Analysis of the expected values and quantification of costs, benefits and risks

This thesis mainly contributes to the second step of the investment planning methodology and provides simulation and mathematical modeling tools which can support investment decisions.

1.4 List of publications

In this section a complete list of published and submitted publications is presented.

Published journal articles in journals listed in Journal Citation Report (JCR):

- *J1*: Khastieva, D., Dimoulkas, I., and Amelin, M., ”Optimal Investment Planning of Bulk Energy Storage Systems,” *Sustainability*, 10(3), 610, 2018. Dina Khastieva planned and wrote the paper under the supervision of Mikael Amelin. Dina Khastieva formulated and simulated mathematical models used in the paper and performed analysis of the results as well as wrote the main part of the text. Ilias Dimoulkas assisted in scenario generation used for renewable generation modeling and assisted in writing the paper.
- *J2*: Khastieva, D, Hesamzadeh, M. R., Vogelsang, I., Rosellón, J., and Amelin, M., ”Value of energy storage for transmission investments,” *Energy Strategy Reviews*, 24, 94-110, 2019 Dina Khastieva planned and wrote the paper under the supervision of Mikael Amelin and Mohammad Reza Hesamzadeh. Dina Khastieva formulated and simulated mathematical models used in the paper and performed analysis of the results as well as wrote the main part of the text. Mohammad Reza Hesamzadeh, Ingo Vogelsang and Juan Rosellón contributed to the paper with economic theory of H-R-G-V incentive mechanism. In addition, Ingo Vogelsang and Juan Roselló assisted in writing the paper and analyzing the results.

- *J3*:Khastieva, D., Hesamzadeh, M. R., Vogelsang, I., and Rosellón, J., ”Transmission Network Investment Using Incentive Regulation: A Disjunctive Programming Approach,” *Networks and Spatial Economics* - Springer (Accepted) Dina Khastieva planned and wrote the paper under the supervision of Mohammad Reza Hesamzadeh. Dina Khastieva formulated and simulated mathematical models used in the paper and performed analysis of the results as well as wrote the main part of the text. Mohammad Reza Hesamzadeh, Ingo Vogelsang and Juan Rosellón contributed to the paper with economic theory of H-R-G-V, H-R-V and ISS incentive mechanisms. In addition, Ingo Vogelsang and Juan Roselló assisted in writing the paper and analysing the results.

Submitted article in journal listed in JCR:

- *J4*: Khastieva, D., Mohammadi S., Hesamzadeh, M. R., Bunn D., ”Optimal Transmission Investment with Regulated Incentives based upon Forward Considerations of Firm and Intermittent Resources with Batteries” *IEEE Transactions on Power Systems* Dina Khastieva planned and wrote the paper under the supervision of Mohammad Reza Hesamzadeh. Dina Khastieva formulated and simulated mathematical models used in the paper and performed analysis of the results as well as wrote the main part of the text. Mohammad Reza Hesamzadeh contributed to the paper with economic theory of ISS incentive mechanism. Saeed Mohammadi helped with writing down the decomposition technique used in the paper. Derek Bunn improved the quality and readability of the paper.

Peer-reviewed articles published in proceeding of conferences:

- *P1* Khastieva, D., and Amelin, M. (2016, July), ”Short-term planning of hydro-thermal system with high wind energy penetration and energy storage,” in IEEE Power and Energy Society General Meeting (pp. 1-5), IEEE, 2016. Dina Khastieva planned and wrote the paper under the supervision of Mikael Amelin. Dina Khastieva formulated and simulated mathematical models used in the paper and performed analysis of the results as well as wrote the main part of the text.

1.5 Research contributions

The contributions of the dissertation can be summarized by the following points:

- *C1* In order to simulate the investment planning process of energy storage that reflects the profit maximizing objective (merchant planning objective) of the corresponding investment planner (energy storage utility) a comprehensive mathematical model is proposed. The model assumes that energy storage capacity size and allocation may affect the capacity development of renewable generation. Moreover, the reverse assumption also applies - the capacity development of renewable generation affects investment decisions of a merchant energy storage utility. Thus, the capacity and allocation decisions of energy storage and wind generation should be modeled jointly. In order to simulate the aforementioned assumption, the model is formulated as a bilevel problem where the upper level simulates merchant energy storage investment planning by considering revenues from energy arbitrage while the lower level is used to simulate market clearance and renewable generation capacity development. The results of the lower level are then considered in the revenue estimation of an energy storage utility while investment decisions in energy storage are considered in renewable generation capacity development and market clearance. This contribution part of publication $J1$ and is partially addressed in publication $J4$.

- *C2* Unlike an energy storage utility, a transmission utility cannot be modeled using a pure merchant approach. The transmission sector is a natural monopoly and consequently should be modeled using a merchant-regulated approach. This means that the mathematical model used to simulate transmission planning should consider the profit maximizing objective of the merchant (profit maximizing) transmission planner as well as regulatory limitations and incentives enforced by the regulator. In this thesis, a comprehensive mathematical model is proposed for a regulated merchant transmission investment planning. The model consists of three planning levels: transmission investment planning, regulatory decision on incentive mechanism and simulation of power system operation, dispatch and market clearance. However, the mathematical model is formulated as a bilevel model where transmission investment planning and regulatory decisions are formulated in the upper level while the lower level simulates operation, planning and market clearance of the power system. This contribution is a part of publications $J2$-$J4$.

- *C3* Energy storage and wind generation are usually considered as complementary technologies. On the other hand, transmission assets and energy storage can be seen either as complements or as substitutes. In any case, transmission investments, energy storage investment and renewable generation capacity investment should be considered together and coordinated to achieve an efficient and socially beneficial planning of the power system. Thus, a comprehensive mathematical model for coordinated investment planning in transmission, energy storage and wind generation is proposed. The model combines the techniques used in contributions *C1* and *C2* and is formulated as a bilevel problem where regulated transmission planning is addressed in the upper level while energy storage and wind generation investment planning is simulated in the lower level using the assumption of perfect competition and perfect information. This contribution is part of publications $J2$ and $J4$.

- *C4* The mathematical models described in *C1*-*C3* are nonlinear and multilevel problems. In order to address these shortcomings of the proposed models additional, reformulation and linearization techniques are proposed. The reformulation and linerization techniques are based on finding the suitable algebraic transformation techniques to find linear and convex equivalents of the nonlinear terms used in the models. This contribution is part of publications $J1$-$J4$.

- *C5* In addition to reformulation and linearizaion technique, the complexities of the models proposed in *C1-C3* are addressed by proposing decomposition techniques. The proposed decomposition techniques are efficiently adapted to the unique structures of the models and are based on a Benders'-like algorithm. Furthermore, the tractability of the proposed decomposition techniques are then accelerated using various customized heuristics. This contribution is part of publications $J3$-$J4$.

1.6 Thesis organization

Chapter 1 is an introduction to investment planning problems in power systems. In Chapter 2, investment planning in energy storage systems and flexibility sources is discussed. Energy storage systems are considered as the most promising flexibility sources which should be integrated into system in order to facilitate growth of renewable generation. In addition, the chapter compares various sources of flexibility such as flexible thermal generation and hydro power and shows that all these sources of flexibility can be modeled in a unified fashion.

As a next step, in Chapter 3, transmission investment planning is presented. The chapter focuses on incentive-based regulation which can support socially optimal transmission investments.

In Chapter 4, comprehensive and detailed mathematical models applied to transmission investment planning are presented. This chapter also includes various reformulation and linearization techniques, as well as novel decomposition algorithms.

Finally, Chapter 5 presents a list of main conclusions. In the Appendix of this thesis, all published and submitted manuscripts are attached in the following order: first, accepted and published manuscripts J1 and J2; second, submitted manuscripts J3 and J4; third, conference paper P1.

CHAPTER 2

Investments in flexibility sources

This chapter provides a broad introduction to publications $J1$,$J2$,$J4$ and $P1$ and partially addresses contribution $C1$. In addition, the chapter provides material which is further used in Chapter 4 to develop mathematical models for investment planning in flexibility assets and partially addresses contribution $C3$ by providing a generalized mathematical formulation for flexibility sources.

Flexibility in power systems is a broad term. The term flexibility is used to describe any ability of a system to adapt to controllable or uncontrollable changes. The term flexibility does not have a unique definition; however, it is widely used in the recent literature especially in the literature focused on variable renewable integration problems. Various authors make an attempt to define flexibility in power systems while the definition varies widely and depends on the target field of the publication. For example, [59] defines flexibility of the power system as the available capacity for a certain ramp capability and ramp duration. In [60], the authors define flexibility as "a power system's ability to respond to short-term variations in demand and supply" and [61] defines flexibility as "the possibility of deploying the available resources to respond in an adequate and reliable way to the load and generation variations during time at acceptable cost". In [62], flexibility is defined as "the ability of a system to deploy its resources to respond to changes in net load, where net load is defined as the remaining system load not served by variable generation". The authors of [63] define flexibility as flexibility of operation and give the following definition: "the ability of a power system to respond to change in demand and supply is a characteristic of all power systems." Reference [64] defines operational flexibility as the "combined available operational flexibility that an ensemble of, potentially very diverse, power system units in a geographically confined grid zone can provide in each time-step during the operational planning, given load demand and Renewable Energy Sources (RES) forecast information, as well as in real-time in case of a contingency".

Despite the difference in definitions, all authors emphasize the importance of presence of flexibility in the power systems especially with large share of variable

Flexibility classification	Reason for flexibility
Short-term flexibility	Wind, solar and load forecast errors Wind, solar and load variability Outages
Medium-term flexibility	Seasonal price fluctuation Seasonal hydro reservoir levels Seasonal load fluctuation Seasonal wind and solar fluctuations
Long-term flexibility	Policy development Capacity markets Load growth Renewable generation growth Generation retirement

Table 2.1: Flexibility classification

renewable generation. Analysis presented in [65] shows that flexibility sources can have additional advantage and exercise market power by acting strategically.

The term flexibility can be used to describe a part of the power system operation as well as generally characterize the system. Defining the term flexibility and distinguishing different types of flexibility is essential to discuss the future development of power systems with high share of renewables. Flexibility in a power system can follow the same classification as power system operation and planning and can be divided into short-, medium- and long-term. Short-term and medium-term flexibility are commonly referred to as operational flexibility and include the ability of the system to balance supply and demand by varying generation, flexible demand, energy storage, or other flexible and dispatchable sources and transmission infrastructure. Short-term flexibility is directly related to balancing needs of the system in real time while medium term flexibility can be used to describe the ability of the system to smooth fluctuations in longer time periods up to one year. In addition, frequency regulation is also a part of short-term flexibility. This dissertation mainly focuses on flexibility of a power system provided in the time frame of five minutes and longer. Frequency regulation is left for power system stability problem analysis. Long-term flexibility of a power system refers to the ability of the system to adapt to long-term changes in the system such as new technology development, forced mandates, newly developed regulation, etc.

The following characteristics may be used as indicators for a lack of flexibility in a power system:

- high price volatility due to binding ramping constraints and line flow limits
- higher prices in an area or node compared to any neighboring area or node
- negative prices

- violation of safety margins of power system assets
- frequent outages / load shedding
- variable renewable generation curtailment
- possibility to exercise market power

A number of different assets can contribute to the flexibility of a power system. A widely discussed and promising technology for future power systems is the family of energy storage technologies. The most important characteristic of energy storage is that it can be used to improve power system flexibility on all time scales and, depending on the technology, to provide a broad variety of services. In the following sections, the specifics of energy storage investments are described, followed by a general description of flexibility sources and generalized modeling methodology.

2.1 Energy storage investments

Rapid growth of renewable generation as well as stricter carbon emission standards make energy storage technologies an attractive solution to solve rising flexibility problems in power systems. Energy storage systems are capable of providing additional flexibility on different time frames to power system operation by charging at peak hours and discharging when additional electricity is required. Such flexibility is very desirable for systems with high shares of variable renewable generation. In addition, energy storage technologies are very fast and can change their output depending on the needs of the system. According to Energy Storage Outlook 2019 provided by BloombergNEF the need in additional storage capacity worldwide is expected to increase from 17 GWh (existing installed capacity as of 2018) to 2,850 GWh by 2040. The forecasted increase in energy storage installations is mostly due to renewable generation capacity increase and additional balancing needs. Similar forecast are provided in [66]. However, aforementioned reports do not explain how investments in energy storage capacities will be procured and what will be business applications.

The problem of storing electricity has been a big issue since the inception of power systems. In order to store electricity it has to be converted into another form of energy such as chemical, mechanical (kinetic or potential), and then converted back to electrical when it is needed. There are different types of energy storage systems already available in the market and several technologies under development stage. They can be classified by the form of energy used to convert to and store electrical energy: mechanic energy, electrochemical energy, thermal energy and electrical energy.

Each type of electricity storage technologies can be considered for providing a range of services to the electric power grid. The range of services is differing based on characteristics of energy storage technology. These characteristics includes:

- Round tip efficiency.
- Self discharge rate
- Power capacity
- Energy capacity
- Response time

Sandia National Laboratories in collaboration with NRECA conducted a vast amount of research on the analysis of different types of energy storage systems and their benefit for different type of applications and provides very comprehensive technical reports on this topic [15]. Moreover, most of technical characteristics as well as cost component of existing energy storage technologies including estimated characteristics of technologies under development could be found in these reports. In addition, Sandia National Laboratories provides a web database with full list of existing projects around the world on energy storage [67].

Reference [68] analyzes influence of large scale energy storage systems such as CAES and Pumped Hydro on economic cost reduction of electric power system. However, some other technologies such as flywheel [69], Sodium-sulfur Battery, Lead acid battery energy storage was successfully tested for providing services to the grid on TSO level and utility level [70], [68], [71].

Energy storage systems have multiple applications and can be beneficial at different levels in the power system. Various literature provide an overview on possible applications and assessment of energy storage benefits. In [14] a comprehensive analysis of possible energy storage applications and suitable energy storage technologies is presented. Applications may vary from energy arbitrage to grid upgrade investments deferral. The most promising applications for energy storage include energy arbitrage, balancing (ancillary) services and renewable generation support. Based on its characteristics energy storage technology can be applicable for different range of services. For example, pumped hydro is the most suitable for energy arbitrage and seasonal storage, battery is suitable for energy arbitrage and ancillary services such as primary control, while flywheels can be applied only for primary regulation and proved to be inefficient and not economical for energy arbitrage due to its high self-discharge. In general, the application range depends on ratio between energy capacity and power capability, self-discharge as well as reaction time. Table 2.2 provides list of possible applications and relative energy storage characteristics required to qualify for each application.

Application	**Low** self-discharge	**Large energy** capacity	**High** power	**Fast** reaction	**High** efficiency
Regulation and balancing (short-term flexibility)			✓	✓	✓
Short-term energy arbitrage (medium-term flexibility)	✓		✓		✓
Long-term energy arbitrage (long-term flexibility)	✓	✓			✓
Transmission support (short- medium- and long-term flexibility)	✓	✓		✓	✓
Black start	✓	✓	✓	✓	

Table 2.2: Energy storage applications and matching characteristics

Different ways how energy storage systems can be used for balancing and regulation, especially in presence of a large amount of variable renewable generation, were studied in [15, 16], while [17] includes benefits of energy storage as a flexibility source. In addition, [18, 19] analyze how energy storage can be beneficial for supporting variable wind power generation and [20] presents benefits of energy storage from a technical point of view and its effect on maximum wind power penetration. A review of modeling techniques of energy storage given different objectives is provided in [21] and includes more than 150 papers on the energy storage assessment subject. The literature provides evidence that energy storage is beneficial for renewable generation support and can be profitable under certain assumptions, however high capital cost is seen as the main obstacle in energy storage market development.

The capital cost of any energy storage technologies consists of two distinct parts. The first part is the component cost (e.g., water reservoir and a dam for pump storage, battery rack for battery, etc.) which determines the energy storage capacity and other characteristics such as as self-discharge. The second part is the cost of power electronics and energy conversion components (e.g., pumps for pump storage, converters for batteries) which determines the power capacity of an energy storage unit. Detailed cost evaluations and calculations for different energy storage technologies are presented in [22, 23] while [72] provides an analysis on future cost development projections. Mature energy storage technologies such as pumped storage and compressed air energy storage are already fully developed, and as a result, the capital cost does not change over time. However, recent interest in battery technologies boosted research and development activities in the sector and capital costs of battery technologies (both, existing and under development) is expected to decrease by 50% by 2030. This decrease in capital cost is expected mostly for electrochemical and electrical energy storage technologies due to the development of new chemicals and materials which will allow to store energy safely and more efficiently. For other types of energy storage technologies, such as mechanical and thermal storage, capital cost is expected to remain on similar levels.

In general, the definition of energy storage system implies technologies which can convert surplus electricity into another form of energy, store it, and then convert it back when it is needed. Mathematically, energy storage operation constraints can be described in general form as:

$$\tilde{e}^{e}_{etk} = \tilde{e}^{e}_{etk-1} - \Gamma \tilde{g}^{e}_{etk} + \frac{1}{\Gamma}\tilde{d}^{e}_{etk} \quad {\scriptstyle \forall e\in\mathcal{E}, t\in\mathcal{T}, k\in\mathcal{K}, s\in\mathcal{S}} \tag{2.1a}$$

$$0 \le \tilde{e}^{e}_{etk} \le E_e \quad {\scriptstyle \forall e\in\mathcal{E}, t\in\mathcal{T}, k\in\mathcal{K}, s\in\mathcal{S}} \tag{2.1b}$$

$$0 \le \tilde{g}^{e}_{etk} \le \epsilon_e E_e a_{etk} \quad {\scriptstyle \forall e\in\mathcal{E}, t\in\mathcal{T}, k\in\mathcal{K}, s\in\mathcal{S}} \tag{2.1c}$$

$$0 \le \tilde{d}^{e}_{etk} \le \epsilon_e E_e (1 - a_{etk}) \quad {\scriptstyle \forall e\in\mathcal{E}, t\in\mathcal{T}, k\in\mathcal{K}, s\in\mathcal{S}}, \tag{2.1d}$$

where $\tilde{e}^{e}_{etk}$, $\tilde{g}^{e}_{etk}$ and $\tilde{d}^{e}_{etk}$ are variables used to simulate the state of charge, charged energy and discharged energy at each operation period k. The operation of the energy storage is limited by the available energy capacity E_e and installed power capability $\epsilon_e E_e, \epsilon_e E_e$. The energy balance constraint (2.1a) represents the state of charge of the energy storage unit. The energy storage will convert surplus of electricity and store it in a different form of energy or in the form of an electromagnetic field and then convert it back when it is demanded [73]. The conversion of electricity into another form of energy brings about some losses. These losses can be represented through efficiency coefficient Γ of the energy storage. Binary variables a_{etk} are used to ensure that energy storage does not charge and discharge at the same time[1].

The available energy capacity and power capability of energy storage can be easily expanded. The majority of energy storage technologies come in different scales and can be easily scaled up or down depending on the need. Any bulk scale energy storage (except pumped hydro) consists of blocks (cells) of small scale energy storage units which together compose an energy storage system.

Merchant energy storage investment planning can be described as:

Maximize Total profit from arbitrage + profit from ancillary services
- Total energy storage investment cost (2.2a)
Subject to:
Energy storage operation constraint (2.2b)
Energy storage investment constraints (2.2c)
Minimize Total operation cost
Subject to: (2.2d)
System energy balance constraints (2.2e)
Power flow constraints (2.2f)
Upper and lower operation limits (2.2g)

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[1] Binary variables a_{etk} can be dropped under certain conditions which are described in Chapter 4

The profit of energy storage depends on energy arbitrage and provision of ancillary services. The revenue in both cases is generated using price differences between charge and discharge. In the case of energy arbitrage, the electricity prices at the moment of charge and discharge are assumed to be cleared using market rules while for ancillary services one of the prices can be predetermined or additional payments can be applied (such as reserved capacity payment). In order for the energy storage operation to be profitable in the short run, the returns of the stored electricity should be greater than sum of the efficiency over price and short run marginal[2] costs of the energy storage technology. Assume, P is the profit of one cycle of an energy storage operation, P_b is the electricity price or payment with which electricity was bought or charged with, P_s is the price or payment with which electricity was sold or discharged with. Γ is the efficiency of an energy storage, θ is self-discharge parameter of an energy storage and c_e is short-run marginal cost. $\delta\tau$ is the time between charge and discharge moments. If self-discharge of an energy storage is low, the profit from one cycle of that energy storage can be measured as:

$$P = P_s - \frac{P_b}{\Gamma} - c_e \tag{2.3}$$

For an energy storage with a high self-discharge parameter such as flywheels the profit of energy storage can be measured as:

$$P = (1 - \theta) * \delta\tau P_s - \frac{P_b}{\Gamma} - c_e \tag{2.4}$$

An energy storage unit will generate profit if and only if $P > 0$.

2.2 Generalized mathematical formulation of flexibility sources

Certain power system technologies are usually considered to be flexible due to high ramp limits and other technical parameters. Any technology which can change generation or demand by a large amount and in a short period of time can be considered a flexibility source. Various existing technologies can be used in the daily power system operation and provide additional flexibility to power systems with high shares of renewable generation. The following existing and commercially available technologies are considered as possible flexibility providers for power systems:

- Hydro power
- Thermal generation

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[2] The majority of energy storage technologies does not use additional fuel to maintain operation of the unit, however each cycle of an energy storage unit usually involves some degradation cost. Thus, short-run marginal costs can be applied in order to reflect degradation and cycling costs of an energy storage unit.

- Combined heat and power
- Flexible demand
- Intermittent renewable generation (can be used for down regulation)

Following the mathematical formulation of energy storage, the aforementioned flexibility sources can be mathematically described in a unified format. A unified mathematical formulation helps to compare flexibility sources and improves the mathematical formulation of investment planning problems when multiple flexibility sources are considered. A compact representation of flexibility technology operation can be formulated as:

$$\tilde{e}^{f}_{ftk} = \tilde{e}^{f}_{ftk-1} - \gamma_f \tilde{g}^{f}_{ftk} + \theta_f \tilde{d}^{f}_{ftk} \quad {\scriptstyle \forall f\in\mathcal{F},t\in\mathcal{T},k\in\mathcal{K}} \tag{2.5a}$$

$$\tilde{e}^{f}_{ftk=0} = \tilde{E}^{0}_{ft} \quad {\scriptstyle \forall f\in\mathcal{F},t\in\mathcal{T},k\in\mathcal{K}} \tag{2.5b}$$

$$0 \leq \tilde{e}^{f}_{ftk} \leq E_f + \widehat{E}_{ft} \quad {\scriptstyle \forall f\in\mathcal{F},t\in\mathcal{T},k\in\mathcal{K}} \tag{2.5c}$$

$$0 \leq \tilde{g}^{f}_{ftk} \leq P^{g}_{f} + \widehat{P}^{g}_{ft} \quad {\scriptstyle \forall f\in\mathcal{F},t\in\mathcal{T},k\in\mathcal{K}} \tag{2.5d}$$

$$0 \leq \tilde{d}^{f}_{ftk} \leq P^{d}_{f} + \widehat{P}^{d}_{ft} \quad {\scriptstyle \forall f\in\mathcal{F},t\in\mathcal{T},k\in\mathcal{K},} \tag{2.5e}$$

where $f \in \mathcal{F}$ indexes all flexibility assets, $t \in \mathcal{T}$ indexes all investment planning periods, $k \in \mathcal{K}$ indexes operation periods. The energy level of a flexibility asset is described by $\tilde{e}^{f}_{ftk}$ (the state of charge variable for energy storage). Decrease and increase in energy level (discharge and charge variables for energy storage) is described by variables $\tilde{g}^{f}_{ftk}$ and $\tilde{d}^{f}_{ftk}$, respectively. Parameters E_f, P^{g}_{f} and P^{d}_{f} are used to set the upper limits for energy level, energy level increase and energy level decrease. Parameter $\tilde{E}^{0}_{ft}$ is used to describe the initial energy level and parameters $\widehat{E}_{ft}$, $\widehat{P}^{g}_{ft}$ and $\widehat{P}^{d}_{ft}$ are added (invested) capacities or power capabilities.

In the following sections, the mathematical representation as well as the derivation to the generalized form is described for each flexibility source separately.

2.2.1 Thermal generation

Thermal generation with fast ramp rate and hydro generation is the most mature and exploited flexibility source available in modern power systems. A broad variety of technologies is available for thermal generation. The flexibility level of dispatchable generation varies along with marginal and capital costs. Additional flexibility from dispatchable generation be obtained by additional capacity or by improving the ramping capability of the generator. Thus, two types of investments can be considered to improve the flexibility level of the power system: investments in installed capacity of a thermal generator; investments in improvements of ramping capability of a thermal generator.

The standard linear mathematical model of a thermal generator can be described as a set of constraints:

$$0 \leq g_{gtk} \leq G_g \quad {\scriptstyle \forall g \in \mathcal{G}, t \in \mathcal{T}, k \in \mathcal{K}} \tag{2.6a}$$

$$- RD_{gt}\delta\tau \leq g_{gtk} - g_{gtk-1} \leq RU_{gt}\delta\tau \quad {\scriptstyle \forall g \in \mathcal{G}, t \in \mathcal{T}, k \in \mathcal{K}} \tag{2.6b}$$

This set of constraints includes capacity limit and ramping constraints. The capacity constraints are presented in (2.6a) and ramping constraints are presented in (2.6b). Variable g_{gtks} is used to describe energy output for each operation hour. Parameters G_g, $RU_{gt}\delta\tau$ and $RD_{gt}\delta\tau$ are used for maximum installed capacity, ramp-up and ramp-down capability, respectively. At each operation period, a thermal generator is scheduled to produce at constant power g_{gtks} for the whole operation period k. Such representation assumes that all the variables and parameters are measured in MWh.

A flexible thermal generator can be represented by the sum of a non-flexible generator with constant output and a fictive energy storage with efficiency equal to one. Ramp-down of a thermal generator can be seen as a combination of constant generation and charge of energy storage while ramp-up can be treated as a combination of constant generation and discharge of an energy storage unit. The charge $\tilde{d}^g_{gtk}$ and discharge $\tilde{g}^g_{gtk}$ of the fictive energy storage then can be described as:

$$\tilde{g}^g_{gtk} = (g_{gtk} - g_{gtk-1}) \quad if((g_{gtk} - g_{gtk-1}) \geq 0)$$
$$\scriptstyle \forall g \in \mathcal{G}, t \in \mathcal{T}, k \in \mathcal{K}$$
$$\tilde{d}^g_{gtk} = (g_{gtk} - g_{gtk-1}) \quad if((g_{gtk} - g_{gtk-1}) \leq 0)$$
$$\scriptstyle \forall g \in \mathcal{G}, t \in \mathcal{T}, k \in \mathcal{K}$$

The generation of a thermal unit g_{gtk} is assumed to be constant and is a decision variable of the first hour of operation $k = 0$. The constant output of the generator also sets the initial state of charge of the fictive energy storage. Then the technical ramping boundaries will create operational limits for charge and discharge of the fictive energy storage unit while maximum generation capacity will create the upper limit for energy storage capacity. Thus, the traditional mathematical formulation of a thermal generator can be represented by an energy storage-like formulation:

$$0 \leq g_{gtk=0} \leq G_g \quad {\scriptstyle \forall g \in \mathcal{G}, t \in \mathcal{T}} \tag{2.7a}$$

$$\tilde{e}^g_{gtk=0} = g_{gtk=0} \quad {\scriptstyle \forall g \in \mathcal{G}, t \in \mathcal{T}} \tag{2.7b}$$

$$\tilde{e}^g_{gtk} = \tilde{e}^g_{gtk-1} - \tilde{g}^g_{gtk} + \tilde{d}^g_{gtk} \quad {\scriptstyle \forall g \in \mathcal{G}, t \in \mathcal{T}, k \in \mathcal{K}} \tag{2.7c}$$

$$0 \leq \tilde{e}^g_{gtk} \leq E_g \quad {\scriptstyle \forall g \in \mathcal{G}, t \in \mathcal{T}, k \in \mathcal{K}} \tag{2.7d}$$

$$0 \leq \tilde{g}^g_{gtk} \leq P_{gt} \quad {\scriptstyle \forall g \in \mathcal{G}, t \in \mathcal{T}, k \in \mathcal{K}} \tag{2.7e}$$

$$0 \leq \tilde{d}^g_{gtk} \leq P_{gt} \quad {\scriptstyle \forall g \in \mathcal{G}, t \in \mathcal{T}, k \in \mathcal{K}} \tag{2.7f}$$

Such representation allows to consider flexibility of thermal generation operation in various time scales and allows for comparison to other flexibility sources such as energy storage.

2.2.2 Hydro power generation

There are three main types of hydro power plants: run-of-river power plants (also known as diversion), power plants with water reservoirs and dams (also known as impoundment) and pumped storage systems. All three types of hydro power plants can be mathematically described by a set of constraints. The operation of the run-of-river plant can be formulated using the same approach as for the thermal generator in (2.7). However, the flexibility of a hydro power plant is limited not by ramping capabilities of the plant but by natural flow limits of the water.

The mathematical formulation of hydro power with reservoirs can be formulated as:

$$m_{htk} = m_{ht-1k} - v_{htk} + u_{htk} - s_{htk} \quad {\scriptstyle \forall h \in \mathcal{H}, t \in \mathcal{T}, k \in \mathcal{K}} \tag{2.8a}$$

$$0 \leq m_{htk} \leq M_h \quad {\scriptstyle \forall h \in \mathcal{H}, t \in \mathcal{T}, k \in \mathcal{K}} \tag{2.8b}$$

$$0 \leq v_{htk} \leq V_h \quad {\scriptstyle \forall h \in \mathcal{H}, t \in \mathcal{T}, k \in \mathcal{K}} \tag{2.8c}$$

$$\overline{g}_{htk} = v_{htk} \Upsilon_h \quad {\scriptstyle \forall h \in \mathcal{H}, t \in \mathcal{T}, k \in \mathcal{K}} \tag{2.8d}$$

$$0 \leq s_{htk} \quad {\scriptstyle \forall h \in \mathcal{H}, t \in \mathcal{T}, k \in \mathcal{K},} \tag{2.8e}$$

where $h \in \mathcal{H}$ is used to index hydro reservoirs, variables m_{htk}, v_{htk} and s_{htk} represent water levels of reservoirs, water outflow and water spillage. The generation of a hydro power plant is simulated through variable $\overline{g}_{htk}$. Parameters M_h and V_h are used to set upper limits for reservoir levels and hydro output.

The mathematical formulation of a hydro power plant with hydro reservoirs is very close to the energy storage formulation (2.1). A hydro power plant stores energy in form of water in the reservoirs. This can be formulated as in (2.8a). The stored water comes from natural inflows u_{htk} into reservoirs. Water reservoir levels and hydro outflow is limited by maximum water reservoir volumes and maximum outflow capability. The upper limits are enforced through constraints (2.8b) and (2.8c). By assuming a constant production equivalent Υ_h the generation of a hydro power plant can be estimated by constraint (2.8d).

Hydro power with reservoir is not considered to be an energy storage unit since it does not fall into the definition of energy storage used in the power system related literature and presented earlier in this chapter. Moreover, unlike most of energy storage technologies, hydro power with a reservoir can produce electricity at a constant rate, even with an empty reservoir and only limited by the water inflow. Thus, similar to thermal generation and run-of-river hydro, a hydro power plant with a reservoir can be considered as a generator with constant power and an energy storage unit. The constant generation of the hydro power plant is equal to the inflow of the reservoir. The flexibility of the hydro power plant with reservoir is then limited by the maximum generation capability of the plant and energy equivalent of the water reservoir capacity. The new mathematical formulation of a hydro power plant with reservoirs can be described as:

$$\tilde{e}^h_{htk} = \tilde{e}^h_{htk-1} - \gamma_f \tilde{g}^h_{htk} + \theta_f \tilde{d}^h_{htk} \quad {\scriptstyle \forall h \in \mathcal{H}, t \in \mathcal{T}, k \in \mathcal{K}} \tag{2.9a}$$

$$\tilde{e}^h_{htk=0} = \tilde{E}^0_{ht} \quad {\scriptstyle \forall h \in \mathcal{H}, t \in \mathcal{T}} \tag{2.9b}$$

$$0 \leq \tilde{e}^h_{htk} \leq E_f \quad {\scriptstyle \forall h \in \mathcal{H}, t \in \mathcal{T}, k \in \mathcal{K}} \tag{2.9c}$$

$$0 \leq \tilde{g}^h_{htk} \leq P^g_f \quad {\scriptstyle \forall h \in \mathcal{H}, t \in \mathcal{T}, k \in \mathcal{K}} \tag{2.9d}$$

$$0 \leq \tilde{d}^h_{htk} \leq P^d_f \quad {\scriptstyle \forall h \in \mathcal{H}, t \in \mathcal{T}, k \in \mathcal{K}} \tag{2.9e}$$

$$0 \leq \overline{g}_{htk} = u_{htk} \Upsilon_h \quad {\scriptstyle \forall h \in \mathcal{H}, t \in \mathcal{T}, k \in \mathcal{K}} \tag{2.9f}$$

2.2.3 Flexible demand

A reformulation of the mathematical formulation of flexible demand into energy storage-like constraints is performed using similar steps as for thermal generation. Demand has a base component which does not depend on price and is defined as $\underline{D}_d$ and a flexible component d_{dtk} with constant utility function α_i. Flexible demand is restricted by maximum contracted flexible load capacity, D_d. In addition, the flexible part of the demand is assumed to be dispatchable and can be changed upwards or downwards. This is represented by two additional variables; $\tilde{g}^d_{dtk}$ and $\tilde{d}^d_{dtk}$. $\tilde{g}^d_{dtk} \geq 0$ and $\tilde{d}^d_{dtk} = 0$ if load is decreased while $\tilde{d}^d_{dtk} \geq 0$ and $\tilde{g}^d_{dtk} = 0$ if load is increased.

$$\begin{aligned} &\tilde{g}^d_{dtk} = (d_{dtk} - d_{dtk-1}) \Upsilon((d_{dtk} - d_{dtk-1}) \leq 0) \\ &\quad {\scriptstyle \forall d \in \mathcal{D}, t \in \mathcal{T}, k \in \mathcal{K}} \\ &\tilde{d}^d_{dtk} = (d_{dtk} - d_{dtk-1}) \Upsilon((d_{dtk} - d_{dtk-1}) \geq 0) \\ &\quad {\scriptstyle \forall d \in \mathcal{D}, t \in \mathcal{T}, k \in \mathcal{K}} \end{aligned}$$

The flexible operation of demand is described by (2.10). Flexible load is assumed to consist of energy limited sources and the deviation from the base load d_{dtk} is limited by E_g which represents the maximum dispatchable demand at each operational period $k < \widehat{K}$ and should be equal to d_{dtk} at the last operational period $k = \widehat{K}$. By doing this, the energy balance constraint ensures that if demand is decreased at time k it will need to be increased at a later time period. Flexibility of dispatchable load is also restricted by technical constraints which does not allow load increase ($\tilde{d}^d_{dtk}$) or decrease ($\tilde{g}^d_{dtk}$) on full capacity through upper limits D_d and G_d. Available flexible load capacity can be increased by contracting additional load from the base component.

$$\tilde{e}^{d}_{dtk} = \tilde{e}^{d}_{dtk-1} - \tilde{g}^{d}_{dtk} + \tilde{d}^{d}_{dtk} \quad {\scriptstyle \forall d\in\mathcal{D},t\in\mathcal{T},k\in\mathcal{K}} \tag{2.10a}$$

$$\tilde{e}^{d}_{dtk=0} = \underline{D}_{d} \quad {\scriptstyle \forall d\in\mathcal{D},t\in\mathcal{T}} \tag{2.10b}$$

$$0 \leq \tilde{e}^{d}_{dtk} \leq E_{g} + \widehat{E}_{gt} \quad {\scriptstyle \forall d\in\mathcal{D},t\in\mathcal{T},k\in\mathcal{K}} \tag{2.10c}$$

$$0 \leq \tilde{d}^{d}_{dtk} \leq D_{d} \quad {\scriptstyle \forall d\in\mathcal{D},t\in\mathcal{T},k\in\mathcal{K}} \tag{2.10d}$$

$$0 \leq \tilde{g}^{d}_{dtk} \leq G_{d} \quad {\scriptstyle \forall d\in\mathcal{D},t\in\mathcal{T},k\in\mathcal{K}} \tag{2.10e}$$

Thus, investment planning models for flexibility sources can be generalized to follow a similar structure as energy storage investment models where efficiencies and capital costs vary dependent on the technology and type of flexibility source.

The application of a generalized mathematical formulation in mathematical models allows to mathematically represent flexibility sources in a compact way and model them as an aggregated energy storage unit. In this way, computational tractability of the mathematical models can be improved and flexibility needs in power system can be determined in an aggregated way. Detailed mathematical models for investment planning for flexibility sources can be found in Chapter 4 of this thesis. In addition, accepted publications $J1$ and $J2$ are also addressing the problem of flexibility investment planning.

CHAPTER 3

Incentive-based transmission investments

This chapter provides a theoretical background to transmission investments planning including a description of several incentive mechanisms. The chapter can be used as complementary material to publications $J2$, $J3$ and $J4$. Furthermore, contributions $C2$ and $C3$ are addressed in this chapter. The provided theoretical background is further used in Chapter 4 to develop mathematical models for investment planning in transmission assets and for coordinated transmission planning.

The aim of any transmission investment planning is to answer the following three questions:

- **where** should a transmission line be built?
- **which** technical characteristics transmission line should have?
- **when** should a transmission line be built?

The answers to these questions may seem straightforward. However, in reality the answer to these questions is complicated due to various uncertainty sources and ambiguities. For example, benefits can be quantified as future cash flows obtained from owning and operating an invested transmission line, or, benefits can be evaluated as total added values to networks participants. An average transmission project takes 10 years to build and practice shows that more than 50% of the projects are delayed or rescheduled [74]. Thus, at the time of completion, the additional transmission capacity can become no longer beneficial and strongly depends on interaction of other system participants such as generation, load and storage. Moreover, reference [74] shows that capital cost estimations of more than 60% of the projects are underestimated. At the same time, reference [52] reports that market based revenues of a transmission company can cover only 25% of the transmission project's total capital cost. As a result, efficient transmission investments require additional incentives from governing entities as well as a properly designed regulatory environment. Furthermore, a growing need for additional wind and solar generation integration requires additional transmission capacities which are well coordinated with the renewable generation investment as well as with flexibility assets such as energy storage.

This chapter addresses all aforementioned challenges associated with transmission investment planning. In Section 3.1 the main principles of transmission investment planning in power systems are described. Benefits and costs of transmission investment are discussed in Section 3.2. Uncertainty sources are presented in Section 3.3. Finally, incentive mechanisms are described in detail in 3.4.

3.1 Transmission investments

The quantification of benefits of an investment project depends on the objectives of a transmission investment as well as on the ownership type. Theoretically, depending on the utility structure of a power system network, a transmission company can be [75]:

- 1. owned and operated by a centralized entity (centrally owned transmission company).
- 2. owned by an independent transmission company and operated based only on market rules (merchant transmission company).
- 3. owned by an independent transmission company and operated based on regulation and market rules (regulated merchant transmission company).

Investment planning of a centrally owned transmission company aims to maximize the social welfare of the network. This means that the transmission investment under the centralized approach should result in the best possible outcome for loads, generators and energy storage. However, such an approach does not take into account market signals from deregulated agents such as generation, load and storage. Thus, in order to achieve the desired outcome, a centrally owned transmission company requires access to all information from all agents which is restricted and protected by regulation. On the other hand, the merchant approach is suitable for deregulated electricity markets and allows to plan investments based purely on market signals. However, the merchant approach has the same drawbacks as the centralized approach. Theoretically, the merchant approach may lead to the same outcome as the centralized one if the perfect information and perfect competition assumptions are satisfied. However, merchant approach have never been successfully implemented in practice. Such an approach is practically hard to implement and was proven to have several economic and regulatory hurdles [76]. Another approach proposed in the literature as well as implemented in various forms in practice is the mixed approach. The mixed approach is commonly known as regulated-merchant approach and combines the benefits of both centralized and merchant approach by capturing price signals from deregulated agents while aiming to maximize socially optimal outcome through regulation and incentives. However, in order to achieve socially optimal results, the proper incentive mechanisms have to be adopted by the regulator.

The regulated-merchant approach assumes that two different independent entities are involved in the decision to invest in transmission assets:

- Regulator.
- Independent Transmission Company or Transmission System Operator (TSO).

The objective of a transmission investment can differ depending on the ownership structure listed above. Ownership structure corresponding to 1,2 and 3 is defined as I, II and III respectively:

- I. Minimization of total investment and system operation costs; maximizing reliability; minimizing expected failures. (centrally owned)
- II. Maximization of market based profits from operation of a transmission asset. (merchant)
- III. Maximization of market based profits from operation of a transmission asset and additional monetary incentives. (regulated merchant)

Despite different objectives of the transmission planning project the main goal of transmission investment is to satisfy the need for additional transmission capacity and to maximize social welfare. Overall, any transmission planning will have to follow social welfare maximizing direction regardless of the type of the objective. The need for additional transmission capacity depends on the current state of the transmission infrastructure as well as the development of generation, demand and development of various electricity market designs. For example, the European goal to develop integrated and harmonized electricity markets is challenged by limited cross border capacities. In order to ensure fair trade between the states while providing sufficient reliability of operation large transmission investments will be required. On the other hand, many electricity markets are subject to internal congestion problems and lack of network investments. For example, in the U.S. (PJM) the market based approach did not obtain the needed transmission investment and the system suffers from severe congestion. Moreover, increased uncertainty of expanding renewable generation results in additional transmission needs and, as a consequence, increased transmission investment cost [77].

In order to decide on additional transmission capacities a comprehensive mathematical model should be developed. Such model will have different levels of complexity depending on the utility structure of the system.

3.2 Benefits, profitability and cost of transmission investments

The benefits of transmission investments can be evaluated in different ways depending on the objectives of the investment planner: (i) improved reliability of the system; (ii) increased profits from the operation of the transmission system; (iii) added societal value.

Improvement of reliability can be measured using various indices such as Loss of Load Probability (LOLP), Expected Energy Not Served (EENS), and many more. However, in the restructured electricity markets monetary benefits are more relevant. The transmission infrastructure owner can generate revenue by providing transmission services to other customers of the system such as generators, loads, and energy storage. Depending on the structure of the system the revenues can be generated through transmission tariffs or other operational charges such as financial transmission rights (FTR).

Transmission tariffs are usually designed in order to recover the maintenance and investment costs of all transmission assets. On the other hand, FTRs correspond to congestion rents. A congestion rent reflects the value of a transmission line in linking two different nodes with different prices.

Apart from congestion rent, the societal benefits can further be quantified by changes in economic indicators such as social welfare and consumer surplus. The change in the total social welfare can be evaluated as the summed surplus of all consumers in the power system. Here, the term consumers includes loads, generation utilities and energy storage utilities. The change in social welfare ΔSW can be quantified as:

$$\Delta SW = \Delta LS + \Delta GS + \Delta SS + \Delta TS - C, \tag{3.1}$$

where ΔLS is the change in total load surplus, ΔGS is the change in total generation surplus, ΔSS is the change in total energy storage surplus, ΔTS is the change in total transmission surplus and C is the total investment costs associated with load utilities, generation utilities, energy storage utilities or the transmission company.

3.3 Uncertainty in transmission planing

Transmission investment planning is subject to various uncertainty sources. Renewable generation and load uncertainty can congest the transmission system, especially, when the penetration is high. On the other hand, outages and other malfunctions of the equipment are also hard to predict and therefore can affect the reliable operation of a power system. Therefore, these uncertainty sources should be taken into account when decisions on transmission line investments are made. Moreover, under the market based transmission investment planning, the cost of the equipment and other economic aspects also have a large impact.

Reliability standards vary for each system and are customarily adapted based on changing characteristics of the system such as, for instance, the generation mix. Reliability standards can be incorporated in any transmission planning by enforcing additional technical constraints on transmission operation and planning. Under centralized planning reliability standards can be seen as the main criteria for investments. However, under market based transmission planning the objective of a transmission investor is profit maximization. Yet, the reliability criteria can be still be enforced by a regulator or a system operator (ISO). The system operator can enforce additional technical reliability constraints which have to be met for the secure operation of the system. A common example for additional constraints is the N-1 criterion. This method will lead to socially optimal investments while reliability criteria are satisfied. From an economic prospective, such reliability constraints may result in additional charges to the consumers. The regulator can relax reliability criteria constraints and promote reliability by assigning monetary weights for each criteria. Thus, the reliability of the power system will become a part of the profit structure of the transmission company.

3.4 Incentive mechanisms

The need for additional incentive mechanisms appears when market signals can no longer guarantee socially beneficial behaviour of a commercial entity. According to [52], congestion rents account for only 25% of the total transmission investment costs. This means that existing market signals such as congestion rents alone cannot provide sufficient incentives for a transmission company to expand the transmission network. Furthermore, market signals are reactive incentives, i.e., price signals can support investment decision only after the scarcity has occurred. The large-scale integration of renewable energy sources requires a significant transmission expansion which should be performed in a proactive way, i.e., before or alongside the expansion of renewable energy capacity. Thus, additional proactive incentives may be necessary to facilitate adequate growth of transmission infrastructure in order to support growth of renewable generation.

Additional incentives are usually controlled by a regulatory entity which can design an appropriate incentive mechanism to facilitate adequate and socially beneficial development of the electricity sector.

Various types of incentive mechanisms were proposed in the literature. However, the effect of incentive mechanisms cannot be analyzed in a unified way and depends on the type of the investment [78]. Two main types of investments can be distinguished:

- Investments which result in end product cost reduction.
- Investments which support infrastructure development.

Transmission investments can be allocated in both categories. Additional transmission capacity may result in electricity price reduction by allowing more efficient operation of cheaper power plants. At the same time the transmission network is the vital infrastructure of any power system.

Similar to the investment classification, two main groups of investment mechanisms can be distinguished:

- Cost-Plus mechanisms. A regulatory entity fixes the rate of return on a particular investment. The regulator sets a maximum allowed charge which a utility can collect from customers to reach a predefined return on investment costs. The charge can include all maintenance and operation costs as well as investment costs. In simple words, the Cost-Plus mechanism allows a utility to reimburse all its costs plus a predefined premium.

- Price-Cap (revenue-cap) mechanisms. A regulatory entity fixes the maximum revenue a utility can earn or maximum price it can charge for a product or service.

Cost-Plus mechanisms are considered to be more suitable for infrastructure investments while Price-Cap mechanism are considered to be more effective for cost reduction investments [79]. This is due to the basic characteristics of each mechanism. The Cost-Plus mechanism reimburses all the costs associated with the investment and operation. As a result the utility has no incentive to reduce investment or operation costs. On the contrary, by setting a maximum boundary on the revenue the regulator implicitly motivates the utility to reduce its costs in order to achieve higher profits. Furthermore, the effectiveness of any incentive mechanism depends on the accuracy of the design and parameter tuning. The effectiveness of incentive regulation can be quantified by its impact on social welfare as illustrated in Fig. 3.1. For example, under the Cost-Plus mechanism, if the rate of return is chosen too low it might result in underinvestment. On the other hand, if the rate of return is selected to be too high then the utility will be incentivized to overinvest. Similarly, if revenue cap is selected too low under the Price-Cap mechanism the firm might go bankrupt and will not have an incentive to operate at all, while, if the price cap is too high there will be no incentive to reduce operational costs. A more comprehensive comparison of these two categories of incentive mechanisms can be found in [80].

References [52] and [53] propose Price-Cap regulatory mechanisms for incentivizing transmission investments of a transmission company. Under certain conditions, these regulatory mechanisms lead to a transmission expansion plan which maximizes social welfare [54]. Reference [55] proposes a reward/penalty regulatory mechanism. In this regulatory mechanism, the regulator rewards the transmission company when the transmission network is expanded and the congestion rents are decreased. Reference [56] proposes an out-turn regulatory mechanism. The out-turn is defined as the difference between actual electricity prices and prices without transmission congestion. The transmission company is responsible for total out-turn cost and any transmission losses. References [54] and [57] extend the work in [52] and propose the incentive-based mechanism for transmission investment. In

Table 3.1: Comparison of different incentive mechanisms.

Advantages:	Cost-Plus	ISS	H-R-G-V
Does not involve subsidies	**yes**	no	**yes**
Guarantees socially optimal investments	no	**yes**	**yes**
Based on market information	no	**yes**	**yes**
Promotes competitive behavior	no	no	**yes**
Simple to model	**yes**	**yes**	**yes**
Convergence to a global solution is guaranteed	**yes**	**yes**	**yes**

this incentive-based regulatory mechanism, the transmission company maximizes its profit (sum of merchandising surplus and a fixed charge) subject to the Price-Cap constraint introduced in [52].

Furthermore, incentive mechanisms can be classified based on the information available to the regulator. Two different scenarios of information availability as well corresponding preferred regulatory schemes can be distinguished:

- The regulator has superiority in accessing all the monetary information in the power system operation and planning of all agents of the system including regulated firms. In this scenario, the regulator can exploit all available information and choose to apply the Bayesian incentive scheme.

- The regulator has limited information on costs structures and operations of a regulated firm (in this thesis, a transmission firm). Under limited available information the regulator cannot apply the Bayesian incentive mechanism efficiently. Thus, a non-Bayesian incentive scheme should be preferred.

Earlier it was mentioned that transmission investment can be classified as system cost reduction investments as well as infrastructure investments. Thus, both Cost-Plus and Price-Cap mechanisms can be considered by a regulator. However, since transmission companies are usually natural monopolies and independent profit maximizing entities only non-Bayesian incentive schemes can be applied to support transmission planning. One of the most famous and oldest non-Bayesian incentive mechanisms is the Incremental Subsidy Surplus (ISS) mechanism. The ISS mechanism employs characteristics of Price-Cap mechanism and incentivizes the transmission company to operate in a social welfare maximizing way. Furthermore, extensive research was performed to combine the main characteristics of Cost-Plus and Price-Cap mechanisms into a single non-Bayesian incentive mechanism [81], [54], [11]. The latter publication [11] presents an H-R-G-V (Hesamzadeh-Rosellon-Gabriel-Vogelsang) mechanism and shows promising performance of the proposed mechanism when applied on transmission investment planning. A comparison of benefits and drawbacks between different incentive mechanisms is presented in Table 3.1

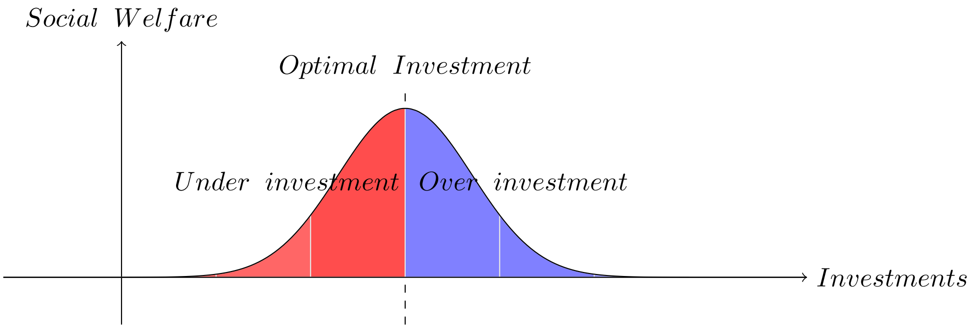

Figure 3.1: Social welfare changes based on accuracy of incentive mechanism design.

3.4.1 Application of the incentive mechanism

Under the incentive-based merchant-regulatory approach the transmission company maximizes its profit by expanding its transmission network while considering regulatory constraints and additional subsides or taxes set by the regulator and depending on incentive mechanisms of choice. In this chapter, three different incentive mechanisms are analyzed: Cost-Plus, ISS and H-R-G-V. All three aforementioned incentive mechanisms require the regulator to design a regulatory constraint and set a fixed fee to reimburse the transmission company based on its performance. The transmission company communicates transmission investment decisions to the regulator and to a system operator (ISO) or equivalent centralized power system operation entity such as a market operator. The ISO dispatches the system and communicates the required information such as load levels, electricity prices, recent capacity changes and system operation costs to the regulator. The regulator uses the information provided by the ISO to recalculate the fixed fee using predefined regulatory constraints and reimburses the transmission company.

For illustrative purposes the following assumptions are taken in this chapter:

- Transmission lines are built at the same time as the decision is taken.
- Generators, loads, and energy storage are independent profit maximizing utilities and comply with perfect competition and perfect information assumptions.
- The transmission company does not share the information on its operation and investment costs.

Then the incentive-based transmission investments can be described as:

$$\begin{aligned} &\textit{Maximize} \;\; \textit{Total congestion rent + Fixed fee} \\ &\qquad\qquad \textit{- Total transmission investment cost} \qquad (3.2a) \\ &\textit{Subject to:} \end{aligned}$$

$$
\begin{aligned}
&\textit{The regulatory constraint} && (3.2b)\\
&\textit{Transmission investment constraints} && (3.2c)\\
&\textit{Maximize social welfare} && (3.2d)\\
&\textit{Subject to:} &&\\
&\quad \textit{Power system operation constraints} && (3.2e)
\end{aligned}
$$

The merchant-regulated transmission company maximizes its total profit which consists of market based revenues (congestion rent) and additional fixed incentive payment (fixed fee). Congested rent is calculated by simulating a market clearing process which can be described as a social welfare maximization problem (3.2d). In this chapter, only the generalized mathematical welfare maximization problem formulation is presented. However, Chapter 4 provides detailed models for centralized market operation and dispatch. The fixed fee is decided by the regulator according to regulatory constraint (3.2b). The regulatory constraint varies depending on the incentive mechanism chosen by the regulator. In the following sections, different incentive mechanisms and the corresponding regulatory constraint are described.

In general form the problem can be mathematically formulated as:

$$
\begin{aligned}
&Maximize \sum_t (1+\beta_t)(\mathbb{E}[\pi^T_{st}] + \Phi_t - \overline{C}_t) && (3.3a)\\
&Subject\ to:\\
&\quad f(\Phi_t) = 0 \ \ \forall t && (3.3b)\\
&\quad Maximize \sum_t (\mathbb{E}[\pi^G_{st}] + \mathbb{E}[\pi^S_{st}] + \mathbb{E}[\pi^T_{st}] + \mathbb{E}[\pi^L_{st}]\\
&\quad Subject\ to: \text{Power system operation constraints} && (3.3c)
\end{aligned}
$$

where $\mathbb{E}[\pi^G_{st}]$ is the expected net profit (including investment costs) of all generation units including wind, thermal, hydro, nuclear and solar. $\mathbb{E}[\pi^T_{st}]$ is the expected short-term net profit of the transmission company obtained by operating the transmission network using competitive market rules and does not include a fixed fee or investment costs. $\mathbb{E}[\pi^L_{st}]$ is the expected total net profit of all loads which includes investment costs and assumes that the utility function of each load is known. $\mathbb{E}[\pi^S_{st}]$ is the expected net profit of energy storage utilities which includes investment costs. $\overline{C}_t$ and Φ_t are the total transmission investment cost and the fixed fee respectively. β_t is the discount rate of the transmission company and is assumed between 0 and 1 ($0 < \beta_t < 1$). The function $f(\Phi_t) = 0$ represents the regulatory constraint and is used to calculate the fixed fee which will be discussed below.

3.4.2 Cost-Plus regulation

Cost-Plus is one of the simplest incentive mechanisms. Cost-Plus incentivizes a transmission company by gradually reimbursing shares of transmission investment costs plus a certain mark-up. The mark-up is usually added in order to guarantee that the transmission company will meet its target return while making investment decisions. In addition, the mark-up is designed such that it reimburses the reduced congestion rent and covers interest rates (opportunity cost of transmission company). The regulatory constraint of the Cost-Plus mechanism can be formulated as:

$$\Phi_t = (1 + R_t)\overline{C}_t \tag{3.4}$$

where R_t is the mark-up coefficient set by the regulator. The fixed fee in the objective function (3.3a) of the transmission company can be replaced by $(1+R_t)\overline{C}_t$. The total profit of the transmission company can then be reformulated as:

$$\sum_t (1 + \beta_t)(\mathbb{E}[\pi^T_{st}] + R_t\overline{C}_t) \tag{3.5}$$

by rewriting the fixed fee according to regulatory constraint (3.4). If the mark-up is chosen such that:

$$R_t\overline{C}_t = \mathbb{E}[\pi^G_{st}] + \mathbb{E}[\pi^T_{st}] + \mathbb{E}[\pi^L_{st}] + \mathbb{E}[\pi^S_{st}] - \overline{C}_t \tag{3.6}$$

then transmission investments can result in social welfare maximizing outcome. However, the tuning of the mark-up to optimality is an informationally complex task and requires the regulator to know also the investment costs of the transmission company. In practice, however, th einvestment costs of the transmision company are usually not made unavailable. Thus, the optimality of the mark-up cannot be guaranteed.

Furthermore, if the mark-up is not tuned to optimality, the transmission company has a strong incentive to over-invest. In (3.5) it can be observed that under the Cost-Plus incentive mechanism the transmission company maximizes the transmission investment costs. In practice, this results in a situation where a more expensive alternative of the investment projects will be chosen by the transmission company. In addition, the Cost-Plus incentive mechanism does not incentivize the transmission company to look forward in its investment planning and, as a result, the Cost-Plus mechanism is unlikely to support proactive transmission planning.

3.4.3 Incremental Subsidy Surplus mechanism (ISS)

The ISS mechanism is a non-Bayesian incentive mechanism and does not require the regulator to know cost functions of the transmission company. Moreover, the ISS mechanism has characteristsics of a Price-Cap incentive mechanism. The main idea behind the ISS incentive mechanism is to reward the transmission company based on its contribution to the change in social welfare by providing an upper limit on its profits through the regulatory constraint. The ISS mechanism calculates the change in social welfare for each investment planning period and redistributes the social welfare according to the contribution of the transmission company. The ISS incentive mechanism can be formulated as:

$$\Phi_t = \Delta\,\mathbb{E}[\pi^G_{st}] + \Delta\,\mathbb{E}[\pi^S_{st}] + \Delta\,\mathbb{E}[\pi^L_{st}] - \mathbb{E}[\pi^T_{st-1}] + \overline{C}_{t-1} \tag{3.7}$$

The regulatory constraint (3.7) of the ISS incentive regulation calculates the fixed fee Φ_t based on total change in social welfare which is equivalent to the sum of changes in generation, energy storage and load profits.
By replacing the fixed fee with the right hand side of constraint (3.7), the objective function of the transmission company (3.3a) becomes:

$$\begin{aligned}
&\sum_t (1+\beta_t)(\mathbb{E}[\pi^T_{st}] + \Phi_t - \overline{C}_t) = \\
&\sum_t (1+\beta_t)(\mathbb{E}[\pi^T_{st}] + \Delta\,\mathbb{E}[\pi^G_{st}] + \Delta\,\mathbb{E}[\pi^S_{st}] + \Delta\,\mathbb{E}[\pi^L_{st}] - \mathbb{E}[\pi^T_{st-1}] - \Delta\overline{C}_t) = \\
&(1+\beta_{t=T})(\mathbb{E}[\pi^T_{st=T}] + \mathbb{E}[\pi^G_{st=T}] + \mathbb{E}[\pi^S_{st=T}] + \mathbb{E}[\pi^G_{st=T}]) + \sum_t (\beta_{t-1} - \beta t)(\mathbb{E}[\pi^T_{st=T}] + \\
&\mathbb{E}[\pi^G_{st=T}] + \mathbb{E}[\pi^G_{st=T}] + \mathbb{E}[\pi^S_{st=T}]) - (1+\beta_{t=0})(\mathbb{E}[\pi^T_{st=0}] - \mathbb{E}[\pi^G_{st=0}] - \mathbb{E}[\pi^L_{st=0}] - \\
&\mathbb{E}[\pi^S_{st=0}]) - \overline{C}_{t=1} - \sum_t (\beta_{t-1} - \beta t)\overline{C}_t - \overline{C}_{t=T} \qquad (3.8)
\end{aligned}$$

In the scope of this thesis, Δ refers to the change of the respective parameter between two consecutive investment planning periods, e.g., before and after a transmission investment. Equation (3.8) shows that transmission investment planning under the ISS incentive regulation has a social welfare maximizing objective. However, the objective of the transmission company highly depends on the discount rate β_t in each investment period. Moreover, ISS incentive regulation guarantees that in the long-run and in the course of the whole investment planning horizon the transmission company will likely invest in social welfare maximizing transmission capacity. By considering future social welfare changes, the ISS mechanism promotes proactive transmission planning. However, ISS does not guarantee a social welfare maximizing outcome for each planning period. Furthermore, while ISS incentive regulation leads to maximum social welfare the proof is dependent on the discount rate which is outside of regulators knowledge. Thus, some complications may arise. For example, if the discount rate is small and does not vary over time, the objective of the transmission company is reduced to

$$\begin{aligned}
&(\mathbb{E}[\pi^T_{st=T}] + \mathbb{E}[\pi^G_{st=T}] + \mathbb{E}[\pi^S_{st=T}] + \mathbb{E}[\pi^G_{st=T}]) - (\mathbb{E}[\pi^T_{st=0}] + \mathbb{E}[\pi^G_{st=0}] + \mathbb{E}[\pi^S_{st=0}] + \\
&\mathbb{E}[\pi^L_{st=0}]) + \overline{C}_{t=1} - \overline{C}_{t=T} \qquad (3.9)
\end{aligned}$$

and at each investment period the revenue of the transmission company consists of the total welfare of the system calculated for that period minus a constant which is the sum of load and generation welfare of the initial investment period.

3.4.4 Hesamzadeh-Rosellon-Gabriel-Vogelsang mechanism (H-R-G-V)

The H-R-G-V incentive mechanism employs similar principles as the ISS incentive mechanism. The H-R-G-V mechanism is non-Bayesian and has Price-Cap characteristics. As in the ISS, the transmission company receives payments corresponding to the change in social welfare. However, unlike the ISS, the H-R-G-V regulation depends recursively on the fixed fee in the preceding time period. This allows the H-R-G-V mechanism to dynamically adjust the fixed fee for each period based on the change in social welfare as well as on the performance of the transmission company during previous years. In comparison, the ISS mechanism can decide on the fixed fee based only on the current performance of the transmission company. The regulatory constraint for transmission investments under the H-R-G-V incentive regulation can be formulated as:

$$\Delta\Phi_t = \Delta\,\mathbb{E}[\pi^G_{st}] + \Delta\,\mathbb{E}[\pi^S_{st}] + \Delta\,\mathbb{E}[\pi^L_{st}] \tag{3.10}$$

The objective function (3.3a) can with this regulatory constraint be reformulated as:

$$\begin{aligned}\sum_t (1+\beta_t)(\mathbb{E}[\pi^T_{st}] + \Phi_t - \overline{C}_t) = \sum_t (1+\beta_t)(\mathbb{E}[\pi^T_{st}] + \Delta\,\mathbb{E}[\pi^G_{st}] + \Delta\,\mathbb{E}[\pi^S_{st}] + \\ \Delta\,\mathbb{E}[\pi^L_{st}] - \Phi_{t-1} - \overline{C}_t) \approx \sum_t (1+\beta_t)(\mathbb{E}[\pi^G_{st}] + \mathbb{E}[\pi^T_{st}] + \mathbb{E}[\pi^L_{st}] + \mathbb{E}[\pi^S_{st}] - \overline{C}_t)\end{aligned} \tag{3.11}$$

The reformulated objective function shows that the regulated objective function of the transmission company is equivalent to the social welfare maximizing objective. The transmission company is rewarded by the sum of changes in load, energy storage and generation surplus in each investment period t. The changes in surplus relate to the benefits that load, energy storage and generation receive from additional transmission capacity. If the change in surplus is larger than the investment costs of the transmission company then the additional transmission capacity will be invested on. Unlike ISS, H-R-G-V regulation does not depend on the discount rate and, as a result, ensures that investments are optimal for each investment planning period. In H-R-G-V, the merchandising surplus and fixed fee of the transmission company reflect the social welfare. As a result, a profit maximizing transmission company will contribute to social welfare maximization and, consequently, to welfare-optimal electricity prices. In addition, by exploiting forward-looking, the H-R-G-V mechanism promotes proactive transmission planning and results in efficient and sustainable transmission investments.

3.4.5 Coordinated investments

This section covers contribution $C3$ of this thesis by extending theoretical formulations of ISS and H-R-G-V regulatory mechanisms to coordinated investment planning in power systems. In the previous subsection, three main incentive mechanisms were described. It was shown that under certain conditions all three mechanisms can result in social welfare maximizing outcome. One of the assumptions taken in the calculation of the social welfare was that installed capacities of generation, load and energy storage remain unchanged. However, the main need in transmission expansion arises due to growing renewable generation and energy storage capacities. Thus, additional investment in wind and energy storage capacities should be taken into account by the regulator when deciding on incentives for transmission companies.

In the case of Cost-Plus mechanism, the contribution of a transmission investment to socially optimal capacity development of wind and energy storage should be taken into account when calculating the mark-up parameter R_t. However, in the case of ISS and H-R-G-V regulation, the regulatory constraints should be adjusted to accommodate the changes in social welfare and investment costs associated with added wind and energy storage capacities.

In general form, the problem of coordinated transmission, wind and energy storage expansion planning can be mathematically formulated as:

$$Maximize \ \sum_t (1+\beta_t)(\mathbb{E}[\pi^T_{st}] + \Phi_t - \overline{C}_t) \tag{3.12a}$$

$$Subject\ to:$$

$$f(\Phi_t) = 0 \ \ \forall t \tag{3.12b}$$

$$Maximize \ \sum_t (\mathbb{E}[\pi^G_{st}] + \mathbb{E}[\pi^S_{st}] + \mathbb{E}[\pi^T_{st}] + \mathbb{E}[\pi^L_{st}] - \widehat{C}_t - \underline{C}_t$$

$$Subject\ to: \tag{3.12c}$$

$$\text{Power system operation constraints} \tag{3.12d}$$

$$\text{Investment constraints} \tag{3.12e}$$

where, $\underline{C}_t$ and $\widehat{C}_t$ are investment costs of wind generators and energy storage units.

The ISS regulatory constraint can be rewritten as:

$$\Phi_t = \Delta\,\mathbb{E}[\pi^G_{st}] + \Delta\,\mathbb{E}[\pi^S_{st}] + \Delta\,\mathbb{E}[\pi^L_{st}] - \mathbb{E}[\pi^T_{st-1}] + \overline{C}_{t-1} - \overline{C}_t - \widehat{C}_t \tag{3.13}$$

Similarly, the H-R-G-V regulatory constraint can be rewritten as:

$$\Delta\Phi_t = \Delta\,\mathbb{E}[\pi^G_{st}] + \Delta\,\mathbb{E}[\pi^S_{st}] + \Delta\,\mathbb{E}[\pi^L_{st}] - \Delta\widehat{C}_t - \Delta\underline{C}_t \tag{3.14}$$

Following the steps described in the previous subsection, it can be shown that both ISS and H-R-G-V incentive mechanism, enforced through constraints 3.13 and 3.14, respectively, will result in socially optimal coordinated investments in wind generation and energy storage units. Considering joint investments in transmission assets, energy storage and wind generation, the social welfare SW_t for time period t can be calculated as:

$$SW_t = \mathbb{E}[\pi^G_{st}] + \mathbb{E}[\pi^T_{st}] + \mathbb{E}[\pi^L_{st}] + \mathbb{E}[\pi^S_{st}] - \overline{C}_t - \widehat{C}_t - \underline{C}_t \tag{3.15}$$

By replacing the fixed fee variable in the objective function of regulated-merchant transmission company (3.12a) with the right hand side of the ISS regulatory constraint (3.13) the following new objective function is obtained:

$$\begin{aligned}
&\sum_t (1+\beta_t)(\mathbb{E}[\pi^T_{st}] + \Delta\,\mathbb{E}[\pi^G_{st}] + \Delta\,\mathbb{E}[\pi^S_{st}] + \Delta\,\mathbb{E}[\pi^L_{st}] - \mathbb{E}[\pi^T_{st-1}] + \overline{C}_{t-1} - \\
&\overline{C}_t - \widehat{C}_t - \overline{C}_t) = \\
&(1+\beta_{t=T})(\mathbb{E}[\pi^T_{st=T}] + \mathbb{E}[\pi^G_{st=T}] + \mathbb{E}[\pi^S_{st=T}] + \mathbb{E}[\pi^G_{st=T}]) + \sum_t (\beta_{t-1} - \beta t)(\mathbb{E}[\pi^T_{st=T}] + \\
&\mathbb{E}[\pi^G_{st=T}] + \mathbb{E}[\pi^G_{st=T}] + \mathbb{E}[\pi^S_{st=T}]) - (1+\beta_{t=0})(\mathbb{E}[\pi^T_{st=0}] - \mathbb{E}[\pi^G_{st=0}] - \mathbb{E}[\pi^L_{st=0}] - \\
&\mathbb{E}[\pi^S_{st=0}]) - \overline{C}_{t=1} - \sum_t (\beta_{t-1} - \beta t)\overline{C}_t - \overline{C}_{t=T} - \widehat{C}_t - \underline{C}_t \approx \\
&SW_{t=T} - SW_{t=1} - \sum_{1<t<T} (\overline{C}_{t=T} - \widehat{C}_t) \qquad (3.16)
\end{aligned}$$

By applying ISS regulatory constraint for coordinated investment planning the objective function of a regulated-merchant transmission company becomes equivalent to maximizing overall social welfare change over the planning horizon and minimizing overall investments in energy storage and wind.

Similarly, when the H-R-G-V regulatory constraint is applied the objective function (3.12a) can be reformulated as:

$$\begin{aligned}
&\sum_t (1+\beta_t)(\mathbb{E}[\pi^T_{st}] + \Delta\,\mathbb{E}[\pi^G_{st}] + \Delta\,\mathbb{E}[\pi^S_{st}] + \Delta\,\mathbb{E}[\pi^L_{st}] - \Delta\widehat{C}_t - \Delta\underline{C}_t - \Phi_{t-1} - \overline{C}_t) \approx \\
&\sum_t (1+\beta_t)(\mathbb{E}[\pi^G_{st}] + \mathbb{E}[\pi^T_{st}] + \mathbb{E}[\pi^L_{st}] + \mathbb{E}[\pi^S_{st}] - \overline{C}_t - \widehat{C}_t - \underline{C}_t) \qquad (3.17)
\end{aligned}$$

By applying the H-R-G-V regulatory constraint for coordinated investment planning, the objective function a regulated-merchant transmission company becomes equivalent to maximization of total social welfare.

3.4.6 Illustrative examples

Consider the two-bus example system presented in Fig. 3.2. The transmission company has to perform an investment planning and can choose to build two transmission lines $M1$ and $M2$. The system consists of two loads $D1$ and $D2$, a wind generator $W1$ and a thermal generator unit $G2$. In this illustrative example it is assumed that transmission expansion planning should be performed over four planning periods. Each planning period represents one year and includes 8760 hours of operation. The maximum demand for the first period is set to 300 MW with a 10 % increase for each consecutive planning period. Wind is also considered as a dispatchable source of energy with zero marginal cost. Moreover, it is assumed that maximum capacities of generators $W1$ and $G2$ remain unchanged for all four planning periods. The production form wind generators is considered to be only source of uncertainty.

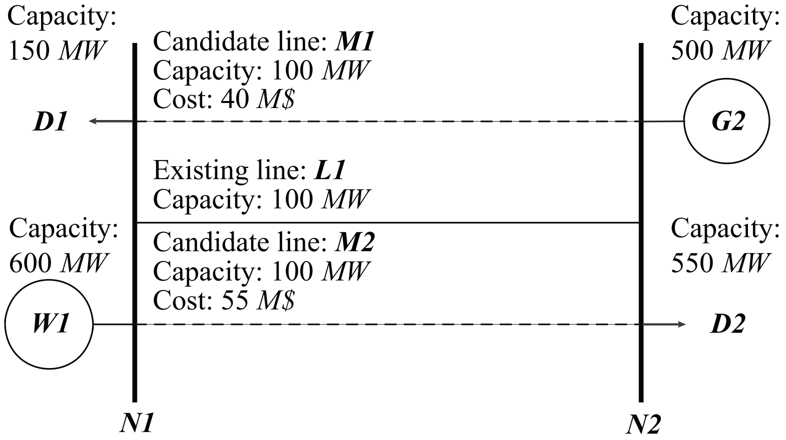

Figure 3.2: Illustration of the two-bus system used for transmission investment planning.

The illustrative example is a reduced version of the full scale model presented in Chapter 4. The results of the illustrative example are applied to the situation where no regulation is used, the case where Cost-Plus mechanism is applied, the case with ISS regulatory constraint, and the case with H-R-G-V regulation. In order to compare the results, an additional example of investment planning with social welfare maximizing objective is performed. The results [1] for each simulation are presented in Table 3.2-Table 3.6. In the case where no regulation is used, no investment in transmission assets are made. On the other hand, in the case where Cost-Plus mechanism is applied the transmission company invests in both lines, even though the investments result in lower social welfare. On the contrary, when H-R-G-V and ISS incentive mechanisms are used, the transmission company invests in $M1$. Moreover, exactly the same investment decisions are made under a centralized social welfare maximizing approach which represents the ideal investment planning. On the other hand, in the case study where no regulation is applied, no transmission investment are made. This result is consistent with the theoretical conclusion provided earlier in this chapter that unregulated investment planning may result in under-investing.

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[1] It should be noted that social welfare results presented in the tables are discounted by interest rate and therefore are decreasing over time.

Table 3.2: Investment results without regulation in the 2-bus system. Tran: Transmission; Inv: Investment.

	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
M1 (1,2)	0	0	0	0	0
M2 (1,2)	0	0	0	0	0
Social Welfare (M$)	38.45	29.1	27.82	25.11	22.4
Wind curtailed (%)	7	5	3	2	1
Tran. Inv. Cost ($)	0	0	0	0	0

Table 3.3: Investment results under the Cost-Plus regulatory mechanism in the 2-bus system. Tran: Transmission; Inv: Investment.

	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
M1 (1,2)	0	**1**	**1**	**1**	**1**
M2 (1,2)	0	**1**	**1**	**1**	**1**
Social Welfare (M$)	38.45	30.4	30.1	29.2	28.7
Wind curtailed (%)	7	1	0	0	0
Tran. Inv. Cost (k$)	0	95 000	0	0	0

Table 3.4: Investment results under the ISS regulatory mechanism in the 2-bus system. Tran: Transmission; Inv: Investment.

	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
M1 (1,2)	0	**1**	**1**	**1**	**1**
M2 (1,2)	0	0	0	0	0
Social Welfare (M$)	38.45	31.2	30.51	29.9	29.1
Wind curtailed (%)	7	1	0	0	0
Tran. Inv. Cost (k$)	0	40 000	0	0	0

Table 3.5: Investment results under the H-R-G-V regulatory mechanism in the 2-bus system. Tran: Transmission; Inv: Investment.

	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
M1 (1,2)	0	**1**	**1**	**1**	**1**
M2 (1,2)	0	0	0	0	0
Social Welfare (M$)	38.45	31.2	30.51	29.9	29.1
Wind curtailed (%)	7	1	0	0	0
Tran. Inv. Cost (k$)	0	40 000	0	0	0

Table 3.6: Investment results under the centralized investments planning in the 2-bus system. Tran: Transmission; Inv: Investment.

	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
M1 (1,2)	0	**1**	**1**	**1**	**1**
M2 (1,2)	0	0	0	0	0
Social Welfare (M$)	38.45	31.2	30.51	29.9	29.1
Wind curtailed (%)	7	1	0	0	0
Tran. Inv. Cost (k$)	0	40 000	0	0	0

In the example above it was assumed that the maximum capacity of wind generator $W1$ remains unchanged for all planning periods. Now, consider a slightly different example system setup which is illustrated in Fig. 3.3. Storage unit $S1$ with installed energy capacity of 50 MWh and 25 MW power capacity is added at node $N2$. In addition, it is assumed that wind investment and energy storage investments can be performed by independent companies alongside transmission investments, i.e., installed capacities of units $W1$ and $S1$ can be increased with the corresponding investment costs of 600 $k\$$ per MW and 1000 $k\$$ per MWh.

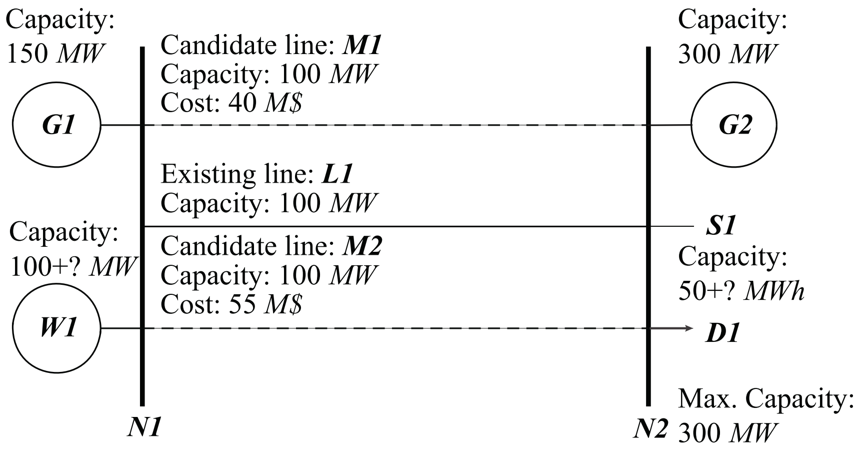

Figure 3.3: Illustration of the two-bus system used for coordinated investment planning.

The results [2] of this illustrative example are presented in Table 3.7 for the unregulated example, in Table 3.8 for Cost-Plus mechanism, in Table 3.9 for ISS mechanism, and in Table 3.10 for H-R-G-V.

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[2] It should be noted that social welfare results presented in tables are discounted by interest rate and therefore are decreasing over time.

Table 3.7: Coordinated investment results without regulation in the 2-bus system. Tran: Transmission; Inv: Investment.

	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
M1 (1,2)	0	0	0	0	0
M2 (1,2)	0	0	0	0	0
Social Welfare (M$)	38.45	30.1	27.82	25.11	22.4
Wind curtailed (%)	0	10	5	3	2
Tran. Inv. Cost ($)	0	0	0	0	0
ES. Inv. Cost (k$)	0	20 000	0	0	0
Wind. Inv. Cost (M$)	0	4.1	0	0	0

Table 3.8: Coordinated investment results under the Cost-Plus regulatory mechanism in the 2-bus system. Tran: Transmission; Inv: Investment.

	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
l1 (1,2)	0	**1**	**1**	**1**	**1**
l2 (1,2)	0	**1**	**1**	**1**	**1**
Social Welfare (M$)	38.45	32.9	32.22	29.9	29.4
Wind curtailed (%)	0	2	1	0.5	0
Tran. Inv. Cost (k$)	0	95 000	0	0	0
ES. Inv. Cost (k$)	0	15 000	0	0	0
Wind. Inv. Cost (M$)	0	3.7	0	0	0

Table 3.9: Coordinated investment results under the ISS regulatory mechanism in the 2-bus system. Tran: Transmission; Inv: Investment.

	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
M1 (1,2)	0	**1**	**1**	**1**	**1**
M2 (1,2)	0	0	0	0	0
Social Welfare (M$)	38.45	33.9	31.44	30.01	29.1
Wind curtailed (%)	0	0.5	0	0	0
Tran. Inv. Cost (k$)	0	40 000	0	0	0
ES. Inv. Cost (k$)	0	25 000	0	0	0
Wind. Inv. Cost (M$)	0	2.1	1.3	0	0

Table 3.10: Coordinated investment results under the H-R-G-V regulatory mechanism in the 2-bus system. Tran: Transmission; Inv: Investment.

	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
M1 (1,2)	0	**1**	**1**	**1**	**1**
M2 (1,2)	0	0	0	0	0
Social Welfare (M$)	38.45	33.9	31.44	30.01	29.1
Wind curtailed (%)	0	0.5	0	0	0
Tran. Inv. Cost (k$)	0	40 000	0	0	0
ES. Inv. Cost (k$)	0	25 000	0	0	0
Wind. Inv. Cost (M$)	0	2.1	1.3	0	0

It can be observed that under the ISS and H-R-G-V mechanisms more efficient investment in wind generation and energy storage are performed. This observation supports the conclusion that ISS incentive mechanism and H-R-G-V mechanism promote a forward-looking approach and result in proactive transmission investment planning. Illustrative examples and case studies for transmission planning and coordinated investment planning applied to larger test systems can be found in publications $J2$, $J3$, and $J4$ of this thesis.

Chapter 4

Mathematical models and derivations

This chapter presents detailed mathematical models which can be used to support investment decision and capacity expansion processes in power systems. First, the mathematical models are described in Section 4.1-Section 4.4. Second, mathematical reformulations and linearizations are proposed in order to simplify the problems and improve computational tractability of the proposed models in Section 4.5. Third, in order to further improve computational tractability of the proposed and reformulated models tailored decomposition techniques are proposed and described in details in Section 4.6. All models presented in this chapter assume that the network consists of an interconnected transmission network, dispatchable loads with predefined utility function, hydro generation, thermal generation, energy storage units, and wind generation.

4.1 Centrally operated dispatch model

The short-term operation of a power system can be simulated in various ways depending on the assumptions about the utility structure, competition, etc. The comprehensive simulation of the short-term operation of a deregulated power system should include detailed simulation of each utility, electricity market, transmission company as well as regulatory entity. However, such comprehensive model will be computationally intractable and consequently not provide any solution or meaningful results. The short-term operation of a power system can be simplified by assuming perfect competition and perfect information. Then, the short-term operation can be reduced to simulation of the system operator (equivalently market operator) and formulated as a centrally operated dispatch model.

In this thesis, it is considered that a power system consists of independent loads, energy storage, generation utilities and an independent transmission company. Furthermore, the power system is operated by a system operator (market operator) under the perfect competition market rules and the assumption of perfect information between system operator, loads, energy storage and generation utilities is valid. In general form the centrally operated dispatch model of a system operator can be described as:

$$
\begin{aligned}
&\underset{\Omega}{Maximize}\ \text{Total gross consumer surplus} && \text{(4.1a)}\\
&Subject\ \ to:\\
&\text{Short-term operational and technical constraints of a power system:}\\
&\quad a.\ \text{Transmission power flow constraints} && \text{(4.1b)}\\
&\quad b.\ \text{Energy storage operation constraints} && \text{(4.1c)}\\
&\quad c.\ \text{Hydro power operation constraints} && \text{(4.1d)}\\
&\quad d.\ \text{Wind generation constraints} && \text{(4.1e)}\\
&\quad e.\ \text{Thermal Generation technical constraints} && \text{(4.1f)}\\
&\quad f.\ \text{Upper and lower limit operational constraints} && \text{(4.1g)}
\end{aligned}
$$

The objective of the centrally operated dispatch model is to ensure that the supply of electricity is equal to the electricity demand at each operational period in the most cost effective way. This objective can be achieved by maximizing the difference between the total benefits obtained by the demand (utility function of demand multiplied by the total demand) and the overall costs of supply (marginal costs of generating and storage units). The objective function can be formulated mathematically as:

$$
\begin{aligned}
&\underset{\Omega}{Maximize} \sum_{t\in\mathcal{T}} \frac{\Psi}{(1+i_t)^{t-1}} \Big(\sum_{s\mathcal{S}k\in\mathcal{K}} \pi_s (\sum_{d\in\mathcal{D}} A_d d_{dtks} - \sum_{g\in\mathcal{G}} C_g\, g_{gtks} - \\
&\sum_{e\in\mathcal{E}} (C_e^{(dh)} \tilde{d}_{etks} + C_e^{(ch)}\ \tilde{g}_{etks})) \qquad \text{(4.2a)}
\end{aligned}
$$

The balance between demand and supply at each node of the system is achieved through power balance constraint:

$$
\begin{aligned}
&\sum_{g\in\mathcal{G}} J_n^{(g)} g_{gtks} + \sum_{w\in\mathcal{W}} W_n^{(w)} \widehat{g}_{wtks} - \sum_{d\in\mathcal{D}} I_n^{(d)} d_{dtks} + \sum_{e\in\mathcal{E}} E_n^{(e)} \tilde{g}_{etks} + \sum_{h\in\mathcal{H}} H_n^{(h)} \overline{g}_{htks} - \\
&\sum_{e\in\mathcal{E}} E_n^{(e)} \tilde{d}_{etks} - \sum_{l\in\mathcal{L}} S_n^{(l)} f_{ltks} + \sum_{l\in\mathcal{L}} R_n^{(l)} f_{ltks} \quad {\scriptstyle \forall n\in\mathcal{N}, t\in\mathcal{T}, k\in\mathcal{K}, s\in\mathcal{S}} \qquad \text{(4.2b)}
\end{aligned}
$$

The dispatch problem of a system operator is also subject to various technical constraints of the transmission network, generators and energy storage units. Transmission network consists of various transmission lines which connect one node of the system to another. Power flows in transmission lines are subject to Kirchhoff's law and consist of active and reactive power. Mathematically the active power flow of transmission line l can be modeled as:

$$f_{ltks} = \frac{R_l}{R_l^2 + X_l^2}[\sum_{n\in\mathcal{N}} S_n^{(l)}\theta_{ntks}^2 - \sum_{n\in\mathcal{N}} S_n^{(l)}\theta_{ntks}R_n^{(l)}\theta_{ntks}cos(\sum_{n\in\mathcal{N}} S_n^{(l)}\sigma_n - \sum_{n\in\mathcal{N}} R_n^{(l)}\sigma)]+$$
$$\frac{X_l}{R_l^2 + X_l^2}sin(\sum_{n\in\mathcal{N}} S_n^{(l)}\sigma_n - \sum_{n\in\mathcal{N}} R_n^{(l)}\sigma_n) \quad {\scriptstyle \forall l\in\mathcal{L},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.2c}$$

where R_l and X_l are resistance and reactance of transmission line l. The power flow formulation (4.2c) is nonlinear. However, the following assumptions[1] can be adopted in order to simplify the formulation to a linear representation of power flows:

- Line resistance can be neglected due to its relatively small numerical value and can be approximated to be equal to 0. $R_l^2 \approx 0$.
- Voltage values can be approximated to be equal to 1 p.u..
- Voltage angle difference between sending and receiving nodes is small. This leads to $sin(S_n^{(l)}\sigma_n - R_n^{(l)}\sigma_n) \approx S_n^{(l)}\sigma - R_n^{(l)}\sigma_n$and $cos(S_n^{(l)}\sigma_n - R_n^{(l)}\sigma_n) \approx 0$.

Using aforementioned assumption the power flow constraint can be reduced to:

$$f_{ltks} = \frac{100}{X_l}(\sum_{n\in\mathcal{N}} S_n^{(l)}\theta_{ntks} - \sum_{n\in\mathcal{N}} R_n^{(l)}\theta_{ntks}) = 0 \quad {\scriptstyle \forall l\in\mathcal{L},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}}. \tag{4.2d}$$

Energy limited assets such as energy storage and hydro power can be modeled through a series of time coupled constraints. Energy storage operation involves keeping track of the state of charge which can be formulated as:

$$q_{etks} = q_{et(k-1)s} - \frac{1}{\Gamma}\tilde{g}_{etks} + \Gamma\tilde{d}_{etks} \quad {\scriptstyle \forall e\in\mathcal{E},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}}. \tag{4.2e}$$

Similarly operation of hydro power plants requires control over the water reservoir levels. The changes in water reservoir levels can be modeled through hydrological balance constraints as:

$$m_{htks} = m_{ht-1ks} - \frac{1}{\Upsilon_h}\overline{g}_{htks} + u_{htks} - s_{htks} \quad {\scriptstyle \forall h\in\mathcal{H},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.2f}$$

Generation, load, energy storage charge and discharge as well as transmission power flows and hydro power reservoir levels have technical limits. These limits can be formulated as upper and lower bounds of the variables.

Transmission power flows are described through variables f_{ltks} which are positive if n is the sending node and negative if n is the receiving node. Upper and lower limit of power flows represent thermal limits of each line and are modeled as:

$$-F_l \leq f_{ltks} \leq F_l \quad {\scriptstyle \forall l\in\mathcal{L},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.2g}$$

---

[1] Resistance and reactance are assumed to be per unit values.

Operation of the hydro power is restricted by technical limits of the turbine

$$0 \leq v_{htks} \leq V_h \quad {\scriptstyle \forall h \in \mathcal{H}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S}}, \tag{4.2h}$$

maximum level of the hydro reservoir

$$0 \leq m_{htks} \leq M_h \quad {\scriptstyle \forall h \in \mathcal{H}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S}} \tag{4.2i}$$

and the maximum water flow capacity of the spillways

$$0 \leq s_{htks} \quad {\scriptstyle \forall h \in \mathcal{H}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S}} \tag{4.2j}$$

Operation of thermal generation is restricted by its maximum capacity

$$0 \leq g_{gtks} \leq G_g \quad {\scriptstyle \forall g \in \mathcal{G}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S}} \tag{4.2k}$$

Similarly, wind generation cannot exceed its maximum installed capacity. However, wind generation output is also restricted by the wind energy available during the operation period. Thus, ϱ_{wtks} parameter is introduced to describe available (foretasted) wind generation as a percentage of known installed capacity. On the other hand, in this model it is assumed that wind generation can be curtailed. Resulting upper and lower limits are described as:

$$0 \leq \widehat{g}_{wtks} \leq (\widehat{G}_w) \varrho_{wtks} \quad {\scriptstyle \forall w \in \mathcal{W}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S}} \tag{4.2l}$$

Energy storage operation is limited by the maximum power capability of an energy storage unit which is considered to be the same both for charge and discharge operation mode. On the other hand, most of energy storage units including battery and pump storage cannot charge and discharge at the same time. Thus, binary variables a_{etks} are introduced to ensure that charge and discharge does not happen simultaneously. Charge and discharge upper and lower limits then can be modeled as:

$$0 \leq \tilde{g}_{etks} \leq a_{etks} \widehat{P}_{et} \quad {\scriptstyle \forall e \in \mathcal{E}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S}} \tag{4.2m}$$

$$0 \leq \tilde{d}_{etks} \leq (1 - a_{etks}) \widehat{P}_{et} \quad {\scriptstyle \forall e \in \mathcal{E}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S}} \tag{4.2n}$$

The state of charge of an energy storage unit cannot exceed maximum energy capacity. Thus an additional constraint is introduced:

$$0 \leq q_{etks} \leq \widehat{E}_{et} \quad {\scriptstyle \forall e \in \mathcal{E}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S}} \tag{4.2o}$$

Loads depend on predefined utility function and can vary accordingly, however, they cannot exceed the predefined maximum level:

$$0 \leq d_{dtks} \leq D_d \quad {\scriptstyle \forall d \in \mathcal{D}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S}} \tag{4.2p}$$

Finally, the voltage of a slack (reference) node is set to be zero.

$$\theta_{ntks} = 0 \ \forall {\scriptstyle t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S}, n = n_1} \tag{4.2q}$$

The decision space of the centrally operated dispatch problem can be summarized as $\Omega = \{d_{dtks}, \tilde{d}_{etks}, \tilde{g}_{etks}, q_{etks}, \overline{g}_{htks}, v_{htks}, m_{htks}, g_{gtks}, \widehat{g}_{wtks}, f_{ltks}, \theta_{ntks} \in \Re\}$

4.2 Merchant energy storage operation and planning model

The objective of a merchant energy storage utility is to determine how much to invest in which asset or technology and where to allocate these investments so the investment target returns are satisfied and the maximum profit is achieved. The problem of a merchant energy storage utility in general form can be described as:

$$\begin{aligned}
&\underset{\Omega}{Maximize}\ \text{Total short-term profits - total investment costs} && (4.3a)\\
&subject\ \ to:\\
&\quad \textit{Short-term operational technical constraints} && (4.3b)\\
&\quad \textit{Investment return targets} && (4.3c)\\
&\quad \textit{centrally operated dispatch:}\\
&\qquad \textit{Minimize}\ \ \textit{Total operation cost} && (4.3d)\\
&\qquad \textit{Subject to:}\\
&\qquad\quad \textit{Power balance} && (4.3e)\\
&\qquad\quad \textit{Power flow constraints} && (4.3f)\\
&\qquad\quad \textit{Generation constraints} && (4.3g)\\
&\qquad\quad \textit{Upper and lower operation limits} && (4.3h)
\end{aligned}$$

The objective function of a merchant energy storage utility consists of summed profits over the whole life-time of an asset or for a reasonable amount of time which will allow recovery of the investment cost minus total investment costs associate with the energy storage project. The profit of an energy storage depends on the business application and consists of overall revenues minus operational costs. In this chapter it is assumed that the main business application of an energy storage unit is energy arbitrage. The profit from energy arbitrage can be modeled as revenues from selling electricity while discharging minus costs from buying electricity while charging and minus additional costs associated with degradation (the case for batteries) or pumping (the case of pumped hydro and compress air energy storage). Total investment costs usually can be divided into two parts. First, investment costs associate with energy capacity of an energy storage unit such as costs of battery rack for batteries or water reservoirs for pumped hydro. Second, investment costs associated with power capability which determines the charge and discharge speed and maximum power an energy storage unit can provide. An example of cost associated with power capability expansion of an energy storage unit is power electronics costs for batteries or pumps and generators for pump storage's. To better reflect the reality of an energy storage investment process in this thesis it is assumed that the investments are performed in discrete manner. This means an energy storage utility can choose between energy storage modules of different technologies, where each module has fixed energy capacity, power capability and other technical parameters such as self-discharge and efficiency. Mathematically the objective function of a merchant energy storage utility can be described as:

$$\underset{x_{et},q_{etks},\tilde{g}_{etks},\tilde{d}_{etks}}{Maximize} \sum_{t,e} \frac{1}{(1+i_t)^{t-1}} (\sum_{k,s} \Psi \pi_s (E_n^{(e)} \lambda_{ntks} (\tilde{g}_{etks} - \tilde{d}_{etks}) - C_e^{(ch)} (\tilde{g}_{etks} + \tilde{d}_{etks}) + FC_{tk} q_{etks} if(k = K)) - (C_{et}^{(E)} + C_{et}^{(P)})(x_{et} - x_{et-1})) \tag{4.4a}$$

The short-term revenues and as a result the maximization of the objective function is subject to short-term operational constraints, investment return targets as well as bidding strategy of the utility in the wholesale electricity market. An energy storage utility has to decide how much charge and discharge maximum capacities should be made available for a central dispatch problem. Moreover, merchant energy storage utility needs to maintain the technical limits of an energy storage unit and keep track of the state of charge of the unit. The operational constraint of energy storage units can be described through energy balance constraints and upper and lower limits of charge, discharge and energy levels at each operational period. Mathematically operational constraints of energy storage system which consists of several energy storage units can be formulated as:

$$q_{etks} = q_{et(k-1)s} - \frac{1}{\Gamma} \tilde{g}_{etks} + \Gamma \tilde{d}_{etks} \quad {\scriptstyle \forall e \in \mathcal{E}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S}} \tag{4.4b}$$

$$0 \leq \widehat{g}_{etks} \leq p_{et} \quad {\scriptstyle \forall e \in \mathcal{E}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S}} \tag{4.4c}$$

$$0 \leq \widehat{d}_{etks} \leq p_{et} \quad {\scriptstyle \forall e \in \mathcal{E}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S}} \tag{4.4d}$$

$$0 \leq q_{etks} \leq e_{et} x_{et} \quad {\scriptstyle \forall e \in \mathcal{E}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S}} \tag{4.4e}$$

$$0 \leq p_{et} 0 \leq p_{et}^{(Inv)} x_{et} \quad {\scriptstyle \forall e \in \mathcal{E}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S}} \tag{4.4f}$$

This model represents only investment decision process while divestment decision is not modelled and assumed to be not an option for an energy storage utility. This means that invested capacities can only increase overtime and never decrease. Non-deceasing property of investment the decision can be represented through additional constraints as:

$$x_{et} \geq x_{et-1} {\scriptstyle \forall t \in \mathcal{T}} \tag{4.4g}$$

On the other hand, in order to maintain risks on an acceptable level any investment planner has certain constraints on expected returns on investments. Such constraint mathematically can be modeled as:

$$\sum_{t,e} \frac{1}{(1+i_t)^{t-1}} (\sum_{k,s} \Psi \pi_s (E_n^{(e)} \lambda_{ntks} (\tilde{g}_{etks} - \tilde{d}_{etks}) - C_e^{(ch)} (\tilde{g}_{etks} + \tilde{d}_{etks}) \geq IR \sum_{t,e} (C_{et}^{(E)} + C_{et}^{(P)})(x_{et} - x_{et-1}) \tag{4.4h}$$

The investment decision process of a merchant energy storage uses spot prices to estimate profits. Spot prices can be simulated using short-term dispatch model presented in Section 4.1. However, since the actual operation of energy storage units are performed by a merchant energy storage utility, the energy storage state of charge operation constraints can be dropped from short-term dispatch model. On the other hand, the upper and lower limit constraints can be reformulated as in 4.5d and 4.5d to represent the bids and offers of an energy storage utility. The bids $\widehat{g}_{etks}$ and offers $\widehat{d}_{etks}$ of an energy storage utility are used to replace maximum and minimum available capacities in equations 4.2m and 4.2n respectively. The bids $\widehat{g}_{etks}$ and offers $\widehat{d}_{etks}$ of an energy storage utility are the limits which can be dispatch by a centrally operated market operator. By doing this, spot prices as well as actual dispatched charge and discharge amounts can be modeled as:

$$\tilde{d}_{etks}, \tilde{g}_{etks}, \lambda_{ntks} \in \tag{4.5a}$$

$$\arg \underset{\Omega_{ST}}{Maximize} \sum_{t \in \mathcal{T}} \frac{\Psi}{(1+i_t)^{t-1}} \Big(\sum_{s \in \mathcal{S}, k \in \mathcal{K}} \pi_s \big(\sum_{d \in \mathcal{D}} A_d d_{dtks} - \sum_{g \in \mathcal{G}} C_g \, g_{gtks} -$$

$$\sum_{e \in \mathcal{E}} (C_e^{(dh)} \tilde{d}_{etks} + C_e^{(ch)} \, \tilde{g}_{etks})) \tag{4.5b}$$

$$Subject\ to \ : \ (4.2b) - (4.2l), (4.2o) - (4.2q) \tag{4.5c}$$

$$0 \leq \tilde{g}_{etks} \leq a_{etks} \widehat{g}_{etks} \ : (\underline{\kappa}_{etks}, \overline{\kappa}_{etks}) \quad \forall e \in \mathcal{E}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S} \tag{4.5d}$$

$$0 \leq \tilde{d}_{etks} \leq (1 - a_{etks}) \widehat{d}_{etks} \ : (\underline{\vartheta}_{etks}, \overline{\vartheta}_{etks}) \quad \forall e \in \mathcal{E}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S} \tag{4.5e}$$

where $\Omega_{ST} = \{d_{dtks}, \tilde{d}_{etks}, \tilde{g}_{etks}, q_{etks}, \overline{g}_{htks}, v_{htks}, m_{htks}, g_{gtks}, \widehat{g}_{wtks}, f_{ltks}, \theta_{ntks} \in \Re\}$

Publication $J1$ utilizes similar model for energy storage investment planning and provides numerical test results which can be used to validate the model presented in this chapter. Publication $J1$ can be found in the Appendix of this thesis.

4.3 Regulated-merchant transmission planning model

Investment planning of a regulated-merchant transmission planner differs from the investment planning of merchant energy storage utility due to additional regulatory measures applied on the transmission revenues. The regulator can incetivize the merchant transmission company to invest in more socially beneficial transmission lines by offering an additional fixed payment (fixed fee) if the investment increased the social welfare. On the other hand the regulator has to decide how to calculate this fixed fee and which incentive mechanism to use. The choice of the regulator on incentive mechanism is a static process and is not influenced by the transmission decisions. Thus, the calculation of the fixed fee can be integrated into the transmission investment planning model. In this section H-R-G-V incentive mechanism is used to simulate calculation of the fixed fee. H-R-G-V incentive mechanism is chosen for illustrative purpose. Similar models can be formulated for other incentive mechanisms such as ISS and Cost-Plus mechanisms by reformulating regulatory constraint according to the incentive mechanism design. In general form the investment planning problem of a merchant-transmission planner can be formulated as:

Maximize: Total congestion rent + Fixed fee
- Total transmission investment cost (4.6a)
Subject to:
H-R-G-V regulatory constraint for each planning period (4.6b)
Linear transmission investment constraints (4.6c)
Centrally operated dispatch:
Minimize: Total operation cost (4.6d)
Subject to:
Power balance (4.6e)
Power flow constraints (4.6f)
Upper and lower operation limits (4.6g)

The theory behind the objective function of regulated-merchant transmission company and regulatory constraint was discussed in Chapter 3, while centrally operated dispatch was described in details in Section 4.1 of this chapter. The objective of the merchant-transmission company is to maximize its total short-term profits plus fixed fee from the regulator minus total investment costs. In short-term transmission company earns by providing transmission services between nodes which have price differences. The short-term profits ($\mathbb{E}[\pi^T_{st}]$) can be calculated as congestion rent which is the summed differences between nodal prices connected by the transmission multiplied by the corresponding generation or load and mathematically can be formulated as:

$$\mathbb{E}[\pi^T_{st}] = \sum_{snk} \lambda_{ntks}(\sum_{dk} I^{(d)}_n d_{dtks} + \sum_{ne} E^{(e)}_n \lambda_{ntks}(\tilde{d}_{etks} - \tilde{g}_{etks}) - \sum_{gk} J^{(g)}_n g_{gtks} - \sum_{wk} W^{(w)}_n \widehat{g}_{wtks}) \forall t \in \mathcal{T} \tag{4.7}$$

The objective function of the transmission company then can be mathematically modeled as:

$$\underset{z_{mt}, y_{mt}}{\text{Maximize:}} \sum_{t \in \mathcal{T}} \frac{\Phi_t + \mathbb{E}[\pi^T_{st}] - \sum_{m \in \mathcal{M}} C^{(T)}_{mt} y_{mt}}{(1 + i_t)^{t-1}} \tag{4.8a}$$

The transmission investment process is simulated using integer variables y_{mt} and z_{mt}. The integer variable y_{mt} represent a decision to invest into a line m at the investment planning period t while z_{mt} represents existence of the line at the investment planning period t. A line m exists only if an investment decision was taken at investment planning period t or earlier. The existence of the line m is modeled as:

$$z_{mt} = \sum_{\widehat{t} \leq t} y_{m,\widehat{t}} \quad {\scriptstyle \forall m \in \mathcal{M}, t \in \mathcal{T} \setminus t_1} \tag{4.8b}$$

Where $\widehat{t}$ are the investment planning periods which happen before or at current investment planning period t. The transmission investment decision is assumed to be irreversible and can be taken only once. This property is modeled through additional transmission investment constraints:

$$\sum_{t \in \mathcal{T}} y_{mt} \leq 1 \quad {\scriptstyle \forall m \in \mathcal{M}, t \in \mathcal{T}} \tag{4.8c}$$

$$z_{mt}, y_{mt} \in \{0, 1\} \tag{4.8d}$$

In addition, the first investment planning period is assumed to be a status-quo period and therefore no investment decision is taken and the fixed fee is also set to zero.

$$z_{mt} = 0 \ {\scriptstyle \forall m \in \mathcal{M}, t = t_1 \in \mathcal{T}} \tag{4.8e}$$

$$\Phi_{(t=t_1)} = 0 \tag{4.8f}$$

The Fixed fee Φ_t is calculated for each investment planning period where investment decision can be taken according to the regulatory constraint designed by the regulator. The regulatory constraint for H-R-G-V mechanism is simulated as:

$$\Delta \Phi_t = \Delta \, \mathbb{E}[\pi^L_{st}] + \Delta \, \mathbb{E}[\pi^G_{st}] + \Delta \, \mathbb{E}[\pi^S_{st}] \ {\scriptstyle \forall t \in \mathcal{T} \setminus t_1} \tag{4.8g}$$

The regulatory constraint evaluates the change in the social welfare caused by the transmission investment decision and compares and sets fixed fee according to the change. The social welfare consist of the generation surplus $\mathbb{E}[\pi^G_{st}]$, load surplus $\mathbb{E}[\pi^L_{st}]$ and energy storage surplus $\mathbb{E}[\pi^S_{st}]$. Generation surplus includes hydro generation, wind generation a thermal generation surpluses and calculated as difference between revenue from selling electricity and costs from generation electricity:

$$\begin{aligned} \mathbb{E}[\pi^G_{st}] = & \sum_{s \in \mathcal{S} g \in \mathcal{G} k \in \mathcal{K}} \Big(\sum_{n \in \mathcal{N}} J^{(g)}_n \lambda_{ntks} g_{gtks} - \Psi C_g g_{gtks} \Big) + \sum_{s \in \mathcal{S} n \in \mathcal{N} w \in \mathcal{W} k \in \mathcal{K}} W^{(w)}_n \lambda_{ntks} \widehat{g}_{wtks} + \\ & \sum_{s \in \mathcal{S} n \in \mathcal{N} h \in \mathcal{H} k \in \mathcal{K}} H^{(h)}_n \lambda_{ntks} \overline{g}_{htks} \forall t \in \mathcal{T} \end{aligned} \tag{4.8h}$$

Similarly, load surplus is calculated as overall difference between benefits of consuming electricity and costs of buying electricity:

$$\mathbb{E}[\pi^L_{st}] = \sum_{s \in \mathcal{S} d \in \mathcal{D} k \in \mathcal{K}} \Big(\Psi A_d d_{dtks} - \sum_{n \in \mathcal{N}} I^{(d)}_n \lambda_{ntks} d_{dtks} \Big) {\scriptstyle \forall t \in \mathcal{T}} \tag{4.8i}$$

Energy storage surplus is calculated as difference between revenues from selling electricity and costs of buying electricity and operational costs.

$$\mathbb{E}[\pi^{S}_{st}] = \sum_{s\in\mathcal{S} n e\in\mathcal{E} k\in\mathcal{K}} (E^{(e)}_{n} \lambda_{ntks} (\tilde{g}_{etks} - \tilde{d}_{etks}) + \Psi (C^{(dh)}_{e} \tilde{d}_{etks} - C^{(ch)}_{e}\ \tilde{g}_{etks}))\forall t \in \mathcal{T} \tag{4.8j}$$

The regulated-merchant transmission investment planning requires additional knowledge on spot prices in order to estimate fixed fee and make an investment decision. The spot prices can be simulated using short-term centrally operated dispatch model. However, the short-term dispatch model presented in Section 4.1 should be updated to include additional invested lines in the dispatch. The candidate lines can be modeled through disjunctive constraint:

$$\begin{bmatrix} \widehat{f}_{mtks} = 0 \\ z_{mt} = 0 \end{bmatrix} \vee \begin{bmatrix} \widehat{f}_{mtks} - \frac{100}{X_m} (\sum_{n\in\mathcal{N}} \overline{S}^{(m)}_{n} \theta_{ntks} - \sum_{n\in\mathcal{N}} \overline{R}^{(m)}_{n} \theta_{ntks}) = 0 \\ z_{mt} = 1 \end{bmatrix}$$

$$\forall m\in\mathcal{M}, t\in\mathcal{T}, k\in\mathcal{K}, s\in\mathcal{S} \tag{4.9}$$

and upper and lower constraint of candidate lines:

$$- \widehat{F}_{m} \leq \widehat{f}_{mtks} \leq \widehat{F}_{m} \quad \forall m\in\mathcal{M}, t\in\mathcal{T}, k\in\mathcal{K}, s\in\mathcal{S} \tag{4.10}$$

Furthermore the power balance constraint also should be update to include power flows of newly invested transmission lines:

$$\sum_{g\in\mathcal{G}} J^{(g)}_{n} g_{gtks} + \sum_{w\in\mathcal{W}} W^{(w)}_{n} \widehat{g}_{wtks} - \sum_{d\in\mathcal{D}} I^{(d)}_{n} d_{dtks} + \sum_{e\in\mathcal{E}} E^{(e)}_{n} \tilde{g}_{etks} + \sum_{h\in\mathcal{H}} \sum_{h\in\mathcal{H}} H^{(h)}_{n} \overline{g}_{htks} -$$
$$\sum_{e\in\mathcal{E}} E^{(e)}_{n} \tilde{d}_{etks} - \sum_{l\in\mathcal{L}} S^{(l)}_{n} f_{ltks} + \sum_{l\in\mathcal{L}} R^{(l)}_{n} f_{ltks} - \sum_{m\in\mathcal{M}} \overline{S}^{(m)}_{n} \widehat{f}_{mtks} +$$
$$\sum_{m\in\mathcal{M}} \overline{R}^{(m)}_{n} \widehat{f}_{mtks} = 0 \ : (\lambda_{ntks}) \quad \forall n\in\mathcal{N}, t\in\mathcal{T}, k\in\mathcal{K}, s\in\mathcal{S} \tag{4.11}$$

By implementing aforementioned modifications in short term dispatch model spot prices, dispatched loads, generation, energy storage charge and discharge can be obtained as:

$$\tilde{d}_{etks}, \tilde{g}_{etks}, d_{dtks}, g_{gtks}, \overline{g}_{htks}, \widehat{g}_{wtks}, \lambda_{ntks} \in$$
$$\arg \underset{\Omega_{TR}}{Maximize} \sum_{t\in\mathcal{T}} \frac{\Psi}{(1+i_t)^{t-1}} \Big(\sum_{s\in\mathcal{S}, k\in\mathcal{K}} \pi_s (\sum_{d\in\mathcal{D}} A_d d_{dtks} - \sum_{g\in\mathcal{G}} C_g\, g_{gtks} -$$
$$\sum_{e\in\mathcal{E}} (C^{(dh)}_{e} \tilde{d}_{etks} + C^{(ch)}_{e}\ \tilde{g}_{etks})) \tag{4.12a}$$

$$Subject\ to\ :\ (4.2b) - (4.2q), (4.18), (4.10) \tag{4.12b}$$

where $\Omega_{TR} = \{d_{dtks}, \tilde{d}_{etks}, \tilde{g}_{etks}, q_{etks}, \overline{g}_{htks}, v_{htks}, m_{htks}, g_{gtks}, \widehat{g}_{wtks}, f_{ltks}, \widehat{f}_{mtks}, \theta_{ntks} \in \Re\}$ The complete transmission investment problem of a regulated-merchant transmission company is then becomes a bilevel stochastic disjunctive problem.

A transmission investment problem of a regulated-merchant transmission company is also described in publication $J3$. Furthermore publication $J2$ contains numerical test results which can be used to validate the model. Publication $J3$ can be found in the Appendix of this thesis.

4.4 Coordinated operation and planning model

Development of transmission, renewable generation or energy storage cannot be evaluated in isolated way. Renewable generation capacity development affects the needs in additional transmission infrastructure as well additional flexibility which can be provided though energy storage. On the other hand, transmission infrastructure and energy storage capacities can be equivalently treated as substitutes or complements. Transmission and energy storage both can support development and integration of variable and uncertain renewable generation. On the other hand, transmission and energy storage cannot fully solve all challenges of renewable generation integration when applied alone. Moreover, both transmission and energy storage can affect electricity price levels and volatility and consequently indirectly influence to each other revenue streams. Thus, in order to achieve the best social welfare maximizing outcome the development of renewable generation, transmission and energy storage should be evaluated in a coordinated manner.
In general form coordinated investment planning of renewable generation, energy storage and transmission can be described as:

Maximize Total congestion rent + Fixed fee
- Total transmission investment cost (4.13a)

Subject to:

(A) Regulatory constraint for each planning period (4.13b)

(B) Linear transmission investment constraints (4.13c)

(C) ISO dispatch and capacity expansion planning (4.13d)

Minimize Total operation cost +
Generation investment costs+Energy Storage Investment costs (4.13e)

Subject to:

Linear generation investment constraints (4.13f)

Linear energy storage investment constraints (4.13g)

Power balance (4.13h)

$$\textit{Power flow constraints} \tag{4.13i}$$
$$\textit{Upper and lower operation limits} \tag{4.13j}$$

The objective as well as the objective function of transmission investment planning problem remains the same as for merchant-transmission investment planning and can be modeled as:

$$\underset{z_{mt},y_{mt}}{\text{Maximize:}} \sum_{t\in\mathcal{T}} \frac{\Phi_t + \mathbb{E}[\pi^T_{st}] - \sum_{m\in\mathcal{M}} C^{(T)}_{mt} y_{mt}}{(1+i_t)^{t-1}} \tag{4.14a}$$

The profit of transmission planner is still calculated as in (4.7). The investment decision constraints can be formulated as:

$$\sum_{t\in\mathcal{T}} y_{mt} \leq 1 \;\; \forall m \in \mathcal{M}, t \in \mathcal{T} \tag{4.14b}$$
$$z_{mt} = 0 \; \forall m \in \mathcal{M}, t = t_1 \in \mathcal{T} \tag{4.14c}$$
$$z_{mt}, y_{mt} \in \{0,1\} \tag{4.14d}$$

On the other hand, additional capacity expansion of energy storage and wind generation has to be reflected in the calculation of the social welfare change. The idea is that transmission expansion should support the most cost efficient capacity decisions on energy storage and wind generation and as a result the calculation of fixed fee should depend on the investment costs. If transmission expansion caused investment in more expensive asset then the fixed fee will be lower, however, if the additional transmission line made it possible to invest in cheaper asset then transmission company will be compensated by higher fixed fee. Thereby, the regulatory constraint should be updated accordingly. H-R-G-V regulatory constraint adapted for coordinated expansion planning can be formulated as:

$$\Phi_{(t=t_1)} = 0 \tag{4.14e}$$
$$\begin{aligned}&\Delta\Phi_t = \Delta\,\mathbb{E}[\pi^L_{st}] + \Delta\,\mathbb{E}[\pi^G_{st}] + \Delta\,\mathbb{E}[\pi^S_{st}] + \\ &P_t(-\sum_{w\in\mathcal{W}} C^{(W)}_{wt}(u_{wt} - u_{w(t-1)}) - \sum_{e\in\mathcal{E}} C^{(E)}_{et}(e_{et} - e_{e(t-1)}) - \\ &\sum_{e\in\mathcal{E}} C^{(P)}_{et}(p_{et} - p_{e(t-1)})) \; \forall t \in \mathcal{T}\backslash t_1\end{aligned} \tag{4.14f}$$

Furthermore, transmission investments have to be coordinated with energy storage and wind generation capacity developments in the system. Under the assumption of perfect competition and perfect information energy storage and wind generation capacity decisions can be combined with centrally operated dispatch and market operation. To do so, the objective function of centrally operated short-term dispatch (4.2a) should be rewritten to include costs of investments into energy storage and wind generation as in $4.17a$. Wind generation investment costs at each investment planning period and for each wind location can be modeled as $C_{wt}^{(W)}(u_{wt}-u_{w(t-1)})$. Energy storage investment costs are modeled for each investment planning period and for each energy storage site as summed investment costs of power electronics components $C_{et}^{(P)}(p_{et}-p_{e(t-1)})$ and investment costs of energy capacity $C_{et}^{(E)}(e_{et}-e_{e(t-1)})$. Upper limit constraint of wind generation (4.2l) and energy storage (4.2l)-(4.2o) should be updated to include additional investment capacities:

$$0\leq\widehat{g}_{wtks}\leq(\widehat{G}_w+u_{wt})\varrho_{wtks}:\ \forall w\in\mathcal{W},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S} \tag{4.15a}$$

$$0\leq\tilde{g}_{etks}\leq a_{etks}(\widehat{P}_{et}+p_{et})\quad \forall e\in\mathcal{E},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S} \tag{4.15b}$$

$$0\leq\tilde{d}_{etks}\leq(1-a_{etks})(\widehat{P}_{et}+p_{et})\quad \forall e\in\mathcal{E},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S} \tag{4.15c}$$

$$0\leq q_{etks}\leq\widehat{E}_{et}+e_{et}\quad \forall e\in\mathcal{E},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S} \tag{4.15d}$$

Availability of invested energy storage and wind generation capacities are enforced through additional investment constraint which ensure that invested capacities are in place at each period of time after the investment decision took place. Energy storage and wind generation investment constraints are modeled as:

$$e_{et}-e_{e(t-1)}\geq 0\ \ \forall e\in\mathcal{E},t\in\mathcal{T} \tag{4.16a}$$

$$p_{et}-p_{e(t-1)}\geq 0\ \ \forall e\in\mathcal{E},t\in\mathcal{T} \tag{4.16b}$$

$$u_{wt}-u_{w(t-1)}\geq 0\ \ \forall w\in\mathcal{W},t\in\mathcal{T} \tag{4.16c}$$

Then, the parameters $\tilde{d}_{etks},\tilde{g}_{etks},d_{dtks},g_{gtks},\overline{g}_{htks},\widehat{g}_{wtks},\lambda_{ntks}$, u_{wt},e_{et},p_{et} used in the transmission planning problem can be obtained as:

$$\begin{aligned}&\tilde{d}_{etks},\tilde{g}_{etks},d_{dtks},g_{gtks},\overline{g}_{htks},\widehat{g}_{wtks},\lambda_{ntks},u_{wt},e_{et},p_{et}\in\\&\arg\underset{\Omega^{CDC}}{Maximize}\sum_{t\in\mathcal{T}}\frac{\Psi}{(1+i_t)^{t-1}}\Big(\sum_{s\in\mathcal{S},k\in\mathcal{K}}\pi_s(\sum_{d\in\mathcal{D}}A_d d_{dtks}-\sum_{g\in\mathcal{G}}C_g\,g_{gtks}-\\&\sum_{e\in\mathcal{E}}(C_e^{(dh)}\tilde{d}_{etks}+C_e^{(ch)}\ \tilde{g}_{etks}))-\frac{1}{(1+i_t)^{t-1}}(\sum_{w\in\mathcal{W}}C_{wt}^{(W)}(u_{wt}-u_{w(t-1)})+\\&\sum_{e\in\mathcal{E}}C_{et}^{(E)}(e_{et}-e_{e(t-1)})+\sum_{e\in\mathcal{E}}C_{et}^{(P)}(p_{et}-p_{e(t-1)}))\end{aligned} \tag{4.17a}$$

The operational constraints of short-term dispatch will remain the same except the the decision space will increase to include capacity decision on candidate energy storage assets and wind generation. Thus, the maximization problem 4.17a is a subject to the following operational constraints:

$$(4.16),(4.2b)-(4.2k),(4.2p)-(4.2q),(4.15) \tag{4.17b}$$

$$(4.18),(4.10) \tag{4.17c}$$

The decision space of the dispatch problem combined with capacity decision problem is $\Omega^{CDC}=\{d_{dtks},\tilde{d}_{etks},\tilde{g}_{etks},q_{etks},\overline{g}_{htks},v_{htks},m_{htks},g_{gtks},\widehat{g}_{wtks},$

$f_{ltks}, \widehat{f}_{mtks}, \theta_{ntks}, u_{wt}, p_{et}, e_{et} \in \Re\}$ In this model energy storage and wind generation capacity decision are considered to be continuous. Due to scailability of wind farms and energy storage systems such assumption will still reflect investment planning in reality. The coordinated investment planning problem is then becomes a bilevel stochastic disjunctive nonlinear problem.

A coordinated investment planning problem for transmission investments and energy storage investments is presented and analyzed in publication $J2$. In publication $J3$ a comprehensive coordinated investment planning problem for transmission, wind and energy storage is presented and applied on numerical test cases. Both, publication $J2$ and publication $J3$, can be found in the Appendix of this thesis.

4.5 Additional mathematical derivations

The problems described above require a long-term forward price curves to evaluate investments. In this thesis the long-term forward curves are simulated using centrally operated dispatch and dispatch coupled with capacity development models (4.2), (4.12) and (4.17). The lower-level models (4.2), (4.12) and (4.17) are solved simultaneously with the respective investment planning problems (4.4),(4.8) and (4.17) and are formulated as a lower level problems. Thus, investment planning models presented in this chapter are stochastic, nonlinear or disjunctive nonlinear bilevel problems and as a result are hard to solve using commercial state-of-the-art solvers such as CPLEX or GUROBI. In this chapter, simple but yet effective reformulation techniques which can be applied on computationally challenging problems such as (4.4),(4.8) and (4.17) are presented. It is shown that bilevel, nonlinear and disjunctive problems can be reformulated into a single-level linear or mixed integer linear equivalent models using simple algebraic transformation and properties of first-order optimality conditions.

For illustrative purposes only one bilevel model from presented above was selected, namely the model (4.8). However, techniques presented in this chapter can be applied to any nonlinear disjunctive bilevel problems with similar properties to (4.8) which is the case for problems (4.4) and (4.8).

4.5.1 McCormic linearization technique for disjunctive constraints

Disjunctive constraints [2] such as constraint (4.18) are complicating constraints since they are nonconvex. Disjunctive constraints can be linearized using McCormic linearization technique also known as big-M reformulation. McCormic linearization technique were well studied in [82] and [83] and allows to reformulate disjunctive constraint into mixed-integer linear constraints with disjunctive parameters (also known as big-M parameters). The choice of disjunctive parameters is critical for mixed-integer linear reformulation of disjunctive constraints. The parameters

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[2] See Section 4.6.1 for more information on disjunctive programming

should be chosen big enough that the original feasibility set does not change and not too big because the reformulated constraints should be as tight as possible in order to avoid computational intractability. If the disjunctive parameter is chosen carefully then the reformulated problem will be equivalent to the original one. Using this technique, the disjunctive constraints (4.18) can be reformulated as linear constraints in (4.19). Disjunctive constraint (4.18) in its original form is written as:

$$\begin{bmatrix} \widehat{f}_{mtks} = 0 \\ z_{mt} = 0 \end{bmatrix} \vee \begin{bmatrix} \widehat{f}_{mtks} - \frac{100}{X_m}(\sum_{n \in \mathcal{N}} \overline{S}_n^{(m)} \theta_{ntks} - \sum_{n \in \mathcal{N}} \overline{R}_n^{(m)} \theta_{ntks}) = 0 \\ z_{mt} = 1 \end{bmatrix}$$
$$\forall m \in \mathcal{M}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S} \qquad (4.18)$$

Disjunctive constraint (4.18) is a nonlinear constraint and enforces the following logic into the decision making:

- if $z_{mt} = 1$ then power flow of line m is determined as: $\widehat{f}_{mtks} - \frac{100}{X_m}(\sum_{n \in \mathcal{N}} \overline{S}_n^{(m)} \theta_{ntks} - \sum_{n \in \mathcal{N}} \overline{R}_n^{(m)} \theta_{ntks}) = 0$
- if $z_{mt} = 0$ then power flow of line m is equal to zero $\widehat{f}_{mtks} = 0$

The same logic can be enforced through a set of linear constraints (4.19). If $z_{mt} = 0$ then equations (4.19c) ensure that $\widehat{f}_{mtks} = 0$. Similarly, if $z_{mt} = 1$ equations (4.19a) and (4.19b) ensure that $\widehat{f}_{mtks} - \frac{100}{X_m}(\sum_{n \in \mathcal{N}} \overline{S}_n^{(m)} \theta_{ntks} - \sum_{n \in \mathcal{N}} \overline{R}_n^{(m)} \theta_{ntks}) = 0$. In this case disjunctive parameter Ξ_m should be chosen big enough so the power flows $\widehat{f}_{mtks}$ are not restricted, meaning disjunctive parameter Ξ_m should be greater or equal to thermal limits of power lines m.

$$\widehat{f}_{mtks} - \frac{100}{X_m}(\sum_{n \in \mathcal{N}} \overline{S}_n^{(m)} \theta_{ntks} - \sum_{n \in \mathcal{N}} \overline{R}_n^{(m)} \theta_{ntks}) \leq$$
$$\Xi_m(1 - z_{mt}) \quad \forall m \in \mathcal{M}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S} \qquad (4.19a)$$
$$\widehat{f}_{mtks} - \frac{100}{X_m}(\sum_{n \in \mathcal{N}} \overline{S}_n^{(m)} \theta_{ntks} - \sum_{n \in \mathcal{N}} \overline{R}_n^{(m)} \theta_{ntks}) \geq$$
$$- \Xi_m(1 - z_{mt}) \quad \forall m \in \mathcal{M}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S} \qquad (4.19b)$$
$$- z_{mt}\Xi_m \leq \widehat{f}_{mtks} \leq z_{mt}\Xi_m \quad \forall m \in \mathcal{M}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S} \qquad (4.19c)$$

The tuning of the disjunctive parameter Ξ_m used in the example above is not complicated since the upper limits of the power flows are known. However, McCormic linearization technique also can be applied to a broader range of disjunctive constraints where upper limits of variables are not known and problem of tuning disjunctive parameter Ξ_m may occur. The problem of tuning disjunctive parameter Ξ_m is discussed in Section 4.6.1 of this chapter. Furthermore, a solution technique which does not involve disjunctive parameter Ξ_m is proposed in Section 4.6.5 of this chapter.

4.5.2 Linearization of energy storage charge and discharge operational constraints

Another complicating constraints of the lower-level problem are energy storage charge and discharge constraints (4.15b)-(4.15c). In order to simulate technical limitation and inability of an energy storage to charge an discharge at the same time additional integer variables are used in constraints (4.15b)-(4.15c). The presence of integer variables in the lower-level problem implies noncovex structure and as a result complicates solution process of the bilevel problem and limits convergence accuracy to the global optima. However, using Lemma 1 it can be shown that for the lower-level problems presented in this thesis integer variables involved in charge and discharge constraints can be dropped and constraints (4.15b)-(4.15c) can be formulated as:

$$0 \leq \tilde{g}_{etks} \leq (\widehat{P}_{et} + p_{et}) \quad {\scriptstyle \forall e \in \mathcal{E}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S}} \tag{4.20a}$$

$$0 \leq \tilde{d}_{etks} \leq (\widehat{P}_{et} + p_{et}) \quad {\scriptstyle \forall e \in \mathcal{E}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S}} \tag{4.20b}$$

The following Lemma[3] for energy storage operation constrains used in the models (4.2), (4.12) and (4.17).

Lemma 1. *The binary variables in the energy storage operation constraints modeled as in (4.15b)-(4.15c) can be dropped without allowing simultaneous charge and discharge operation of the energy storage system in the models of the same or similar structure as in (4.2). This means that relaxed LP formulation of (4.2) without charge and discharge binary variables is equivalent to the mixed integer LP formulation with charge and discharge binary variables.*

Proof. Assume that the binary variables are not in place (the problem (4.2) is formulated as an LP problem and equations (4.15b)-(4.15c) are replaced with (4.20)) but charge and discharge happen simultaneously, i.e., $\tilde{d}_{etks} > 0$ and $\tilde{g}_{etks} > 0$. This implies that KKT optimality conditions can be derived for relaxed LP formulation of (4.2). In addition, since charge and discharge limit constraints are nor binding, Lagrangian multipliers of constraints (4.15b)-(4.15c) will be equal to zero, $\underline{\kappa}_{etks} = 0$ and $\underline{\vartheta}_{etks} = 0$. Using stationary conditions (4.21a) and (4.21b) of the relaxed LP model of 4.2:

$$\frac{-\Psi}{(1+i_t)^{t-1}} \pi_s C_e^{(ch)} - \sum_{n \in \mathcal{N}} E_n^{(e)} \lambda_{ntks} + \Gamma \tau_{etks} + \underline{\vartheta}_{etks} - \overline{\vartheta}_{etks} = 0 \; {\scriptstyle \forall e \in \mathcal{E}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S}} \tag{4.21a}$$

$$\frac{-\Psi}{(1+i_t)^{t-1}} \pi_s C_e^{(dh)} + \sum_{n \in \mathcal{N}} E_n^{(e)} \lambda_{ntks} - \frac{1}{\Gamma} \tau_{etks} + \underline{\kappa}_{etks} - \overline{\kappa}_{etks} = 0 \; {\scriptstyle \forall e \in \mathcal{E}, t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S}} \tag{4.21b}$$

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[3] Lemma 1 is an extended version of the Lemma presented in publication *J*4. Lemma 1 and its proof is extended to the mathematical formulations of energy storage which accounts for round-trip efficiencies.

the following equality constraints can be derived

$$\sum_{n\in\mathcal{N}} E_n^{(e)}\lambda_{ntks} \overset{(4.21a)}{=} -\frac{\Psi}{(1+i_t)^{t-1}}\pi_s C_e^{(ch)} + \Gamma\tau_{etks} + \underline{\vartheta}_{etks} - \overline{\vartheta}_{etks}$$

$$\overset{(4.21b)}{=} \frac{\Psi}{(1+i_t)^{t-1}}\pi_s C_e^{(dh)} + \frac{1}{\Gamma}\tau_{etks} - \underline{\kappa}_{etks} + \overline{\kappa}_{etks} \quad {\scriptstyle \forall e\in\mathcal{E},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}}. \tag{4.22a}$$

Previously it was assumed that $\tilde{d}_{etks}>0$ and $\tilde{g}_{etks}>0$ which leads to (4.22b).

$$-\frac{\Psi\pi_s}{(1+i_t)^{t-1}}(C_e^{(dh)} + C_e^{(ch)}) + (\Gamma - \frac{1}{\Gamma})\tau_{etks} = \overline{\vartheta}_{etks} + \overline{\kappa}_{etks} \quad {\scriptstyle \forall e\in\mathcal{E},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.22b}$$

Under the assumption $\tilde{d}_{etks} > 0$ and $\tilde{g}_{etks} > 0$ the sum of $\overline{\vartheta}_{etks} + \overline{\kappa}_{etks}$ on the right-hand side of the equation (4.22b) will be either 0 or a strictly positive while the expression $-P_t\Psi\pi_s C_e^{(dh)} - P_t\Psi\pi_s C_e^{(ch)} + (\Gamma - \frac{1}{\Gamma})\tau_{etks}$ on the left-hand side is strictly negative. This leads us to contradiction and to the conclusion that the assumption $\tilde{d}_{etks} > 0$ and $\tilde{g}_{etks} > 0$ does not hold. Thus, energy storage will not charge and discharge at the same time and at least one of the variables $\tilde{d}_{etks}$ or $\tilde{g}_{etks}$ should be equal to zero in the optimal solution. Furthermore, LP equivalent reformulation is a relaxation of the original MILP, meaning the solution of the LP equivalent ($SW_{LP}(\boldsymbol{y}^*)$) is greater than or equal to the original MILP solution ($SW_{MILP}(\boldsymbol{x}^*)$), where $\boldsymbol{y}^*$ and $\boldsymbol{x}^*$ are optimal solution vectors of the original MILP and the LP equivalent. On the other hand, since it was proved that the disjunctive property of constraints (4.15b)-(4.15c) are maintained in $\boldsymbol{y}^*$, the following inequalities hold $SW_{MILP}(\boldsymbol{y}^*) \leq SW_{MILP}(\boldsymbol{x}^*))$. Therefore, $SW_{MILP}(\boldsymbol{y}^*) \leq SW_{MILP}(\boldsymbol{x}^*) \leq SW_{LP}(\boldsymbol{y}^*))$. Moreover, since the SW_{MILP} and SW_{LP} are linear functions, $SW_{MILP}(\boldsymbol{x}^*) = SW_{LP}(\boldsymbol{y}^*)$ and $\boldsymbol{x}^* = \boldsymbol{y}^*$. □

Using Lemma 1 and McCormic linearization technique, the lower-level disjunctive problem (4.17) can be transformed to an equivalent LP models.

4.5.3 Single-level equivalent reformulation for bilevel models

By employing McCorminc linearization technique for disjunctive constraints and Lemma 1, the mathematical model (4.17) is transformed into an equivalent linear problem 4.23:

$$\underset{\Omega^{CDC}}{Maximize} \sum_{t\in\mathcal{T}} \frac{\Psi}{(1+i_t)^{t-1}} \Big(\sum_{s\in\mathcal{S},k\in\mathcal{K}} \pi_s (\sum_{d\in\mathcal{D}} A_d d_{dtks} - \sum_{g\in\mathcal{G}} C_g\, g_{gtks} -$$

$$\sum_{e\in\mathcal{E}} (C_e^{(dh)}\tilde{d}_{etks} + C_e^{(ch)}\ \tilde{g}_{etks})) - \frac{1}{(1+i_t)^{t-1}} (\sum_{w\in\mathcal{W}} C_{wt}^{(W)}(u_{wt} - u_{w(t-1)}) + \tag{4.23a}$$

$$\sum_{e\in\mathcal{E}} C_{et}^{(E)}(e_{et}-e_{e(t-1)}) + \sum_{e\in\mathcal{E}} C_{et}^{(P)}(p_{et}-p_{e(t-1)}))$$

$$Subject\ \ to:$$

$$(4.16)(4.2b)-(4.2l),(4.2o)-(4.2q) \tag{4.23b}$$

$$(4.19),(4.10),(4.20) \tag{4.23c}$$

Where, $\Omega^{CDC} = \{d_{dtks}, \tilde{d}_{etks}, \tilde{g}_{etks}, q_{etks}, \overline{g}_{htks}, v_{htks}, m_{htks}, g_{gtks}, \widehat{g}_{wtks}, f_{ltks}, \widehat{f}_{mtks}, \theta_{ntks}, u_{wt}, p_{et}, e_{et} \in \Re\}$ Since (4.23) is a linear problem then the Karush-Kuhn-Taker (KKT) optimality conditions are necessary and sufficient [84]. Thus, the optimal solution of (4.23) can be equivalently reformulated as a set of primal, dual and complementary constraints. Furthermore, a set of primal, dual and complementary constraints can be equivalently described as a set of primal and dual constraints and strong duality condition. The reformulation steps based on optimality conditions are illustrated in Fig. 4.1. Assume that a linear problem with objective function f, equality constraints $h(y) = 0$ and inequality constraints $g(y) \leq 0$ exists. Then, the linear problem can be equivalently reformulated as its KKT conditions. KKT conditions of an optimization problem consist of primal constraints ($h(y) = 0$ and $g(y) \leq 0$) of the optimization, Stationary conditions (which are also known as dual constraints ($\bigtriangledown f(y) + \lambda \bigtriangledown g(y) + \mu \bigtriangledown h(y) = 0$)) and Complementary slackness conditions ($\mu g(y) = 0$). Primal constraints are original constraint of the optimization problem while dual constraints are constraints of the dual problem of the optimization problem and correspond to primal variables. By reformulating the optimization problem as a set of primal and dual constraint we ensure that the solution of the set of constraints is feasible in primal and in dual optimization problems. Furthermore, the Duality Theorem (see [85] for more details and the proof) proves that if the solution of an optimization problem is optimal then variables in primal problem complement constraints in dual problem and vice versa. The Duality Theorem implies that if dual variable is strictly greater than zero then corresponding primal constraint is binding. This relationship between primal and dual variables and constraints is enforced by Complementary slackness conditions. Thus, the global optimal point of a linear optimization problem can be found not only by solving the optimization problem but by solving a set of constraints: primal constraint; stationary conditions and complementary slackness constraints.

Complementary slackness conditions, however, are nonlinear and therefore might complicate solution process. On the other hand, complementary slackness conditions can be equivalently enforced by a strong duality condition (a constraint which ensures that the objective function of primal problem is equal to the objective function of the dual problem $f = f^{dual}$), which is linear. Thus, a linear optimization problem can be equivalently reformulated as a set of linear constraints: primal constraints, stationary conditions and complementary slackness constraints.

Figure 4.1: Reformulation steps from bilevel model to single-level equivalent model

$$
\begin{array}{lclcl}
Step\ \ 1 & & Step\ \ 2 & & Step\ \ 3 \\
Optimization & \equiv & KKT\ \ conditions: & \equiv & KKT\ \ conditions: \\
\underset{y}{Min} f & & h(y)=0 & & h(y)=0 \\
\text{S.t:} & & g(y)\leq 0 & & g(y)\leq 0 \\
h(y)=0\ :(\lambda) & & \{Stationary\ \ conditions\}: & & \{Stationary\ \ conditions\} \\
g(y)\leq 0\ :(\mu) & & \bigtriangledown f(y)+\lambda\bigtriangledown g(y)+\mu\bigtriangledown h(y)=0 & & \bigtriangledown f(y)+\lambda\bigtriangledown g_{LL}(y)+\mu\bigtriangledown h(y)=0 \\
 & & \{Complimentary\ \ slackness\ \ conditions\} & & \{Strong\ \ duality\ \ condition\} \\
 & & \mu g(y)=0 & & f=f^{dual} \\
 & & \mu\geq 0 & & \mu\geq 0
\end{array}
$$

The stationary and complementary slackness conditions of the problem (4.23) are derived in (4.24) and (4.25) respectively.

$$\frac{\Psi\pi_s}{(1+i_t)^{t-1}}A_d-\sum_{n\in\mathcal{N}}I_n^{(d)}\lambda_{ntks}+\underline{\omega}_{dtks}-\overline{\omega}_{dtks}=0 \quad \forall d\in\mathcal{D},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S} \tag{4.24a}$$

$$\frac{-\Psi\pi_s}{(1+i_t)^{t-1}}C_g+\sum_{n\in\mathcal{N}}J_n^{(g)}\lambda_{ntks}+\underline{\nu}_{gtks}-\overline{\nu}_{gtks}=0 \quad \forall g\in\mathcal{G},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S} \tag{4.24b}$$

$$\frac{-\Psi\pi_s}{(1+i_t)^{t-1}}C_e^{(ch)}-\sum_{n\in\mathcal{N}}E_n^{(e)}\lambda_{ntks}+\Gamma\tau_{etks}+\underline{\vartheta}_{etks}-\overline{\vartheta}_{etks}=0 \quad \forall e\in\mathcal{E},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S} \tag{4.24c}$$

$$\frac{-\Psi\pi_s}{(1+i_t)^{t-1}}C_e^{(dh)}+\sum_{n\in\mathcal{N}}E_n^{(e)}\lambda_{ntks}-\frac{1}{\Gamma}\tau_{etks}+\underline{\kappa}_{etks}-\overline{\kappa}_{etks}=0 \quad \forall e\in\mathcal{E},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S} \tag{4.24d}$$

$$-\tau_{etks}+\tau_{et(k+1)s}+\underline{\rho}_{etks}-\overline{\rho}_{etks}=0 \quad \forall e\in\mathcal{E},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S} \tag{4.24e}$$

$$\sum_{n\in\mathcal{N}}W_n^{(w)}\lambda_{ntks}+\underline{\kappa}_{ftks}-\overline{\kappa}_{ftks}=0 \quad \forall w\in\mathcal{W},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S} \tag{4.24f}$$

$$\sum_{n\in\mathcal{N}}R_n^{(l)}\lambda_{ntks}-\sum_{n\in\mathcal{N}}S_n^{(l)}\lambda_{ntks}+\sigma_{ltks}+\underline{\sigma}_{ltks}-\overline{\sigma}_{ltks}=0 \quad \forall l\in\mathcal{L},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S} \tag{4.24g}$$

$$-\sum_{n\in\mathcal{N}}\overline{S}_n^{(m)}\lambda_{ntks}+\sum_{n\in\mathcal{N}}\overline{R}_n^{(m)}\lambda_{ntks}+\underline{\varrho}_{mtks}-\overline{\varrho}_{mtks}+$$

$$\underline{\gamma}_{mtks}-\overline{\gamma}_{mtks}+\underline{\xi}_{mtks}-\overline{\xi}_{mtks}=0 \quad \forall m\in\mathcal{M},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S} \tag{4.24h}$$

$$-\frac{100}{X_l}\sum_{l\in\mathcal{L}}S_n^{(l)}\sigma_{ltks}+\frac{100}{X_l}\sum_{l\in\mathcal{L}}R_n^{(l)}\sigma_{ltks}+\xi_{n=1tks}-$$

$$\frac{100}{X_m}\sum_{m\in\mathcal{M}}\overline{S}_n^{(m)}\underline{\varrho}_{mtks}+\frac{100}{X_m}\sum_{m\in\mathcal{M}}\overline{R}_n^{(m)}\underline{\varrho}_{mtks}+$$

$$\frac{100}{X_m}\sum_{m\in\mathcal{M}}\overline{S}_n^{(m)}\overline{\varrho}_{mtks}-\frac{100}{X_m}\sum_{m\in\mathcal{M}}\overline{R}_n^{(m)}\overline{\varrho}_{mtks}=0 \quad {\scriptstyle \forall n\in\mathcal{N},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.24i}$$

$$\frac{-1}{(1+i_t)^{t-1}}C_{et}^{(E)}+\kappa_{et}-\kappa_{et+1}+\sum_{k\in\mathcal{K},s\in\mathcal{S}}\overline{\rho}_{etks}=0 \quad {\scriptstyle \forall e\in\mathcal{E},t\in\mathcal{T}} \tag{4.24j}$$

$$\frac{-1}{(1+i_t)^{t-1}}C_{et}^{(P)}+\vartheta_{et}-\vartheta_{et+1}+\sum_{k\in\mathcal{K},s\in\mathcal{S}}\overline{\kappa}_{etks}+\sum_{k\in\mathcal{K},s\in\mathcal{S}}\overline{\vartheta}_{etks}=0 \quad {\scriptstyle \forall e\in\mathcal{E},t\in\mathcal{T}} \tag{4.24k}$$

$$\frac{-1}{(1+i_t)^{t-1}}C_{wt}^{(W)}+\eta_{wt}-\eta_{wt+1}+\sum_{k\in\mathcal{K},s\in\mathcal{S}}\overline{\kappa}_{ftks}\varrho_{wtks}=0 \quad {\scriptstyle \forall w\in\mathcal{W},t\in\mathcal{T}} \tag{4.24l}$$

$$u_{wt}\eta_{wt}=u_{w(t-1)}\eta_{wt} \quad {\scriptstyle \forall w\in\mathcal{W},t\in\mathcal{T}} \tag{4.25a}$$

$$e_{et}\kappa_{et}=e_{e(t-1)}\kappa_{et} \quad {\scriptstyle \forall e\in\mathcal{E},t\in\mathcal{T}} \tag{4.25b}$$

$$p_{et}\vartheta_{et}=p_{e(t-1)}\vartheta_{et} \quad {\scriptstyle \forall e\in\mathcal{E},t\in\mathcal{T}} \tag{4.25c}$$

$$\begin{aligned}&(\widehat{f}_{mtks}-\frac{100}{X_m}(\sum_{n\in\mathcal{N}}\overline{S}_n^{(m)}\theta_{ntks}-\sum_{n\in\mathcal{N}}\overline{R}_n^{(m)}\theta_{ntks}))\overline{\varrho}_{mtks}=\\&\Xi_m(1-z_{mt})\overline{\varrho}_{mtks} \quad {\scriptstyle \forall m\in\mathcal{M},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}}\end{aligned} \tag{4.25d}$$

$$\begin{aligned}&-(\widehat{f}_{mtks}-\frac{100}{X_m}(\sum_{n\in\mathcal{N}}\overline{S}_n^{(m)}\theta_{ntks}-\sum_{n\in\mathcal{N}}\overline{R}_n^{(m)}\theta_{ntks}))\underline{\varrho}_{mtks}=\\&\Xi_m(1-z_{mt})\underline{\varrho}_{mtks} \quad {\scriptstyle \forall m\in\mathcal{M},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}}\end{aligned} \tag{4.25e}$$

$$f_{ltks}\overline{\sigma}_{ltks}=F_l\overline{\sigma}_{ltks} \quad {\scriptstyle \forall n\in\mathcal{N},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.25f}$$

$$-f_{ltks}\underline{\sigma}_{ltks}=F_l\underline{\sigma}_{ltks} \quad {\scriptstyle \forall n\in\mathcal{N},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.25g}$$

$$\widehat{f}_{mtks}\overline{\gamma}_{mtks}=\widehat{F}_m\overline{\gamma}_{mtks} \quad {\scriptstyle \forall m\in\mathcal{M},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.25h}$$

$$-\widehat{f}_{mtks}\underline{\gamma}_{mtks}=\widehat{F}_m\underline{\gamma}_{mtks} \quad {\scriptstyle \forall m\in\mathcal{M},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.25i}$$

$$-\widehat{f}_{mtks}\underline{\xi}_{mtks}=z_{mt}\Xi_m\underline{\xi}_{mtks} \quad {\scriptstyle \forall m\in\mathcal{M},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.25j}$$

$$\widehat{f}_{mtks}\overline{\xi}_{mtks}=z_{mt}\Xi_m\underline{\xi}_{mtks} \quad {\scriptstyle \forall m\in\mathcal{M},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.25k}$$

$$g_{gtks}\underline{\nu}_{gtks}=0 \quad {\scriptstyle \forall g\in\mathcal{G},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.25l}$$

$$g_{gtks}\overline{\nu}_{gtks}=G_g\overline{\nu}_{gtks} \quad {\scriptstyle \forall g\in\mathcal{G},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.25m}$$

$$\widehat{g}_{wtks}\underline{\kappa}_{ftks}=0 \quad {\scriptstyle \forall w\in\mathcal{W},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.25n}$$

$$\widehat{g}_{wtks}\overline{\kappa}_{ftks}=(\widehat{G}_w+u_{wt})\varrho_{wtks}\overline{\kappa}_{ftks} \quad {\scriptstyle \forall w\in\mathcal{W},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.25o}$$

$$\tilde{g}_{etks}\underline{\kappa}_{etks}=0 \quad {\scriptstyle \forall e\in\mathcal{E},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.25p}$$

$$\tilde{g}_{etks}\overline{\kappa}_{etks}=(p_{et}+\widehat{P}_{et})\overline{\kappa}_{etks} \quad {\scriptstyle \forall e\in\mathcal{E},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.25q}$$

$$\tilde{d}_{etks}\underline{\vartheta}_{etks}=0 \quad {\scriptstyle \forall e\in\mathcal{E},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.25r}$$

$$\tilde{d}_{etks}\overline{\vartheta}_{etks}=(p_{et}+\widehat{P}_{et})\overline{\vartheta}_{etks} \quad {\scriptstyle \forall e\in\mathcal{E},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.25s}$$

$$q_{etks}\underline{\rho}_{etks}=0 \quad {\scriptstyle \forall e\in\mathcal{E},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.25t}$$

$$q_{etks}\overline{\rho}_{etks} = (e_{et} + \widehat{E}_{et})\overline{\rho}_{etks} \quad {\scriptstyle \forall e\in\mathcal{E},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.25u}$$

$$d_{dtks}\underline{\omega}_{dtks} = 0 \quad {\scriptstyle \forall d\in\mathcal{D},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.25v}$$

$$d_{dtks}\overline{\omega}_{dtks} = D_d\overline{\omega}_{dtks} \quad {\scriptstyle \forall d\in\mathcal{D},t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}} \tag{4.25w}$$

On the other hands, using duality theorem complementary slackness conditions (4.25) can be enforced through strong duality condition 4.26:

$$\begin{aligned}
&\sum_{t\in\mathcal{T}} P_t\langle \sum_{s\in\mathcal{S},k\in\mathcal{K}} \pi_s\Psi(\sum_{d\in\mathcal{D}} A_d d_{dtks} - \sum_{g\in\mathcal{G}} C_g\ g_{gtks})- \\
&\sum_{e\in\mathcal{E}}(C_e^{(dh)}\tilde{d}_{etks} + C_e^{(ch)}\ \tilde{g}_{etks}) - P_t\sum_{e\in\mathcal{E}} C_{et}^{(E)}(e_{et} - e_{e(t-1)})- \\
&P_t\sum_{e\in\mathcal{E}} C_{et}^{(P)}(p_{et} - p_{e(t-1)})\rangle = \sum_{t\in\mathcal{T}}\langle\sum_{d\in\mathcal{D}} D_d\overline{\omega}_{dtks} + \sum_{g\in\mathcal{G}} G_g\overline{\nu}_{gtks} + \sum_{w\in\mathcal{W}} \widehat{G}_w\varrho_{wtks}\overline{\kappa}_{ftks} + \\
&\sum_{e\in\mathcal{E}}(\widehat{P}_{et}\overline{\vartheta}_{etks} + \widehat{P}_{et}\overline{\kappa}_{etks} + \widehat{E}_{et}\overline{\rho}_{etks}) + \sum_{l\in\mathcal{L}} F_l(\underline{\sigma}_{ltks} + \overline{\sigma}_{ltks}) + \\
&\sum_{m\in\mathcal{M}} \widehat{F}_m(\underline{\gamma}_{mtks} + \overline{\gamma}_{mtks}) + \\
&\Xi_m(1 - z_{mt})(\overline{\varrho}_{mtks} + \underline{\varrho}_{mtks}) + \Xi_m z_{mt}(\overline{\xi}_{mtks} + \underline{\xi}_{mtks})\rangle
\end{aligned} \tag{4.26}$$

By reformulating lower-level problem (4.17) as a combination of primal feasibility constraints, dual feasibility constraints and a strong duality condition the bilevel problem (4.14) can be transformed to a one-level equivalent formulation:

$$\underset{z_{mt},y_{mt}}{\text{Maximize}} \sum_{t\in\mathcal{T}} \frac{\Phi_t + \mathbb{E}[\pi_{st}^T] - \sum_{m\in\mathcal{M}} C_{mt}^{(T)} y_{mt}}{(1+i_t)^{t-1}} \tag{4.27a}$$

$$\textit{Subject to}:$$

$$z_{m,t=1} = 0\ \forall m \tag{4.27b}$$

$$z_{mt} = \sum_{\widehat{t}\leq t} y_{m,\widehat{t}}\,\forall m, \forall t \geq 2 \tag{4.27c}$$

$$\sum_{t\in\mathcal{T}} y_{mt} \leq 1\ \forall m, \forall t \tag{4.27d}$$

$$\Phi_{t=1} = 0 \tag{4.27e}$$

$$\begin{aligned}
&\Delta\Phi_t = \Delta\,\mathbb{E}[\pi_{st}^L] + \Delta\,\mathbb{E}[\pi_{st}^G] + \Delta\pi_t^W + \Delta\,\mathbb{E}[\pi_{st}^S] + \\
&P_t(-\sum_{w\in\mathcal{W}} C_{wt}^{(W)}(u_{wt} - u_{w(t-1)}) - \sum_{e\in\mathcal{E}} C_{et}^{(E)}(e_{et} - e_{e(t-1)})- \\
&\sum_{e\in\mathcal{E}} C_{et}^{(P)}(p_{et} - p_{e(t-1)}))\ \forall t\geq 2
\end{aligned} \tag{4.27f}$$

$$(4.16)(4.2b) - (4.2l), (4.2o) - (4.2q) \tag{4.27g}$$

$$(4.19), (4.10), (4.20) \tag{4.27h}$$

$$(4.26), (4.24) \tag{4.27i}$$

$$\begin{aligned}&\underline{\omega}_{dtks}, \overline{\omega}_{dtks}, \underline{\nu}_{gtks}, \overline{\nu}_{gtks}, \underline{\kappa}_{ftks}, \overline{\kappa}_{ftks}, \sigma_{ltks},\\ &\overline{\xi}_{mtks}, \overline{\lambda}_{ntks}, \underline{\lambda}_{ntks} \geq 0\end{aligned} \tag{4.27j}$$

$$z_{mt}, y_{mt} \in \{0, 1\} \tag{4.27k}$$

4.5.4 Linearization using algebraic transformations and KKT conditions

In the previous section it was shown that bilevel models such as (4.4), (4.8) and (4.14) can be transformed into one level equivalent model formulations as in example (4.27). However, in the example (4.27) the problem still remains non convex due to nonlinear terms in the upper-level. In this section it is shown that in some cases these terms can be transformed into equivalent linear terms by using simple algebraic transformations and optimality conditions. The proposed transformations follow similar logic as transformations presented in the appendix of [11] and publications $J1$-$J4$. Using KKT conditions of the problem 4.23 it can be proved that the term

$$\begin{aligned}&\sum_{n \in \mathcal{N} d \in \mathcal{D}} I_n^{(d)} \lambda_{ntks} d_{dtks} - \sum_{n \in \mathcal{N} g \in \mathcal{G}} J_n^{(g)} \lambda_{ntks} g_{gtks} +\\ &\sum_{n \in \mathcal{N} e \in \mathcal{E}} E_n^{(e)} \lambda_{ntks} (\tilde{d}_{etks} - \tilde{g}_{etks}) - \sum_{n \in \mathcal{N} w \in \mathcal{W}} W_n^{(w)} \lambda_{ntks} \widehat{g}_{wtks}\end{aligned} \tag{4.28}$$

is equal to

$$\sum_{l \in \mathcal{L}} F_l (\overline{\sigma}_{ltks} + \underline{\sigma}_{ltks}) + \sum_{m \in \mathcal{M}} \widehat{F}_m (\overline{\gamma}_{mtks} + \underline{\gamma}_{mtks}) \forall t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S} \tag{4.29}$$

The initial bilinear expression is stated as:

$$\begin{aligned}&\sum_{n \in \mathcal{N}, d \in \mathcal{D}} I_n^{(d)} \lambda_{ntks} d_{dtks} - \sum_{n \in \mathcal{N}, g \in \mathcal{G}} J_n^{(g)} \lambda_{ntks} g_{gtks} -\\ &\sum_{n \in \mathcal{N}, w \in \mathcal{W}} W_n^{(w)} \lambda_{ntks} + \sum_{n \in \mathcal{N}, e \in \mathcal{E}} E_n^{(e)} \lambda_{ntks} (\tilde{d}_{etks} - \tilde{g}_{etks}) \widehat{g}_{wtks}\end{aligned} \tag{4.30}$$

The nodal prices can be extracted from these terms, i.e.,

$$\sum_{n \in \mathcal{N}} \lambda_{ntks} \underbrace{\left(\begin{array}{c} \sum_{d \in \mathcal{D}} I_n^{(d)} d_{dtks} + \sum_{ne} E_n^{(e)} (\tilde{d}_{etks} - \tilde{g}_{etks}) - \\ \sum_{g \in \mathcal{G}} J_n^{(g)} g_{gtks} - \sum_{w \in \mathcal{W}} W_n^{(w)} \widehat{g}_{wtks} \end{array} \right)}_{L1} \forall t \in \mathcal{T}, k \in \mathcal{K}, s \in \mathcal{S} \tag{4.31}$$

The term L1 also appears in the power flow constraint (4.11) and can thus be replaced by the sum of the power flows:

$$\begin{aligned}&\sum_{l\in\mathcal{L}}\lambda_{ntks}(-\sum_{n\in\mathcal{N}}S_n^{(l)}f_{ltks}+\sum_{n\in\mathcal{N}}R_n^{(l)}f_{ltks})+\\&\sum_{m\in\mathcal{M}}\lambda_{ntks}(-\sum_{n\in\mathcal{N}}\overline{S}_n^{(m)}\widehat{f}_{mtks}+\sum_{n}\overline{R}_n^{(m)}\widehat{f}_{mtks})=\\&\sum_{l\in\mathcal{L}}f_{ltks}\underbrace{(-\sum_{n\in\mathcal{N}}S_n^{(l)}\lambda_{ntks}+\sum_{n\in\mathcal{N}}R_n^{(l)}\lambda_{ntks})}_{L2}+\\&\sum_{m\in\mathcal{M}}\widehat{f}_{mtks}\underbrace{(-\sum_{n\in\mathcal{N}}\overline{S}_n^{(m)}\lambda_{ntks}+\sum_{n}\overline{R}_n^{(m)}\lambda_{ntks})}_{L3}{\scriptstyle\forall t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}}\end{aligned}\tag{4.32}$$

Terms L2 and L3 are parts of stationary condition constraints (4.24g) and (4.24h) respectively. Thus L2 and L3 equivalently can be represented as a linear combination of dual variables from constraints (4.24g) and (4.24h):

$$\begin{aligned}&\sum_{l\in\mathcal{L}}f_{ltks}(\overline{\sigma}_{ltks}-\underline{\sigma}_{ltks}-\sigma_{ltks})+\sum_{m\in\mathcal{M}}\widehat{f}_{mtks}(\underline{\varrho}_{mtks}-\overline{\varrho}_{mtks}+\\&\underline{\gamma}_{mtks}-\overline{\gamma}_{mtks}+\underline{\xi}_{mtks}-\overline{\xi}_{mtks}){\scriptstyle\forall t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}}\end{aligned}\tag{4.33}$$

Using complementary slackness conditions (4.25d)-(4.25k) and stationary condition (4.24i) constraint (4.33) can be equivalently reformulated as:

$$\begin{aligned}&\sum_{l\in\mathcal{L}}F_l(\overline{\sigma}_{ltks}+\underline{\sigma}_{ltks})+\sum_{m\in\mathcal{M}}\widehat{F}_m(\overline{\gamma}_{mtks}+\underline{\gamma}_{mtks})+\\&\sum_{m\in\mathcal{M}}\underbrace{z_{mt}\Xi_m(\underline{\xi}_{mtks}+\overline{\xi}_{mtks})}_{T1}+\\&\sum_{m\in\mathcal{M}}\underbrace{\Xi_m(1-z_{mt})(\overline{\varrho}_{mtks}+\underline{\varrho}_{mtks})}_{T2}{\scriptstyle\forall t\in\mathcal{T},k\in\mathcal{K},s\in\mathcal{S}}\end{aligned}\tag{4.34}$$

The terms $T1=z_{mt}\Xi_m(\underline{\xi}_{mtks}+\overline{\xi}_{mtks})$ and $T2=(1-z_{mt})(\overline{\varrho}_{mtks}+\underline{\varrho}_{mtks})$ include the disjunctive parameters Ξ_m and used to formulate power flow constraints of candidate transmission lines (4.19a)-(4.19c) are complicated because they include variables both from the upper and lower level problems and are thus nonlinear. However, each of these terms are always equal to zero. If the disjunctive parameters are tuned properly, i.e., large enough that they do not limit power flows on accepted candidate lines but small enough to avoid poorly conditioned matrices, then the constraints (4.19c) will never be binding. Similar reasoning was used in [11] to drop disjunctive parameters from the objective function. However, terms $T1$ and

$T2$ cannot be drop if they are located elsewhere than only in the objective function. Instead, equations $T1 = 0$ and $T2 = 0$ have to be enforced.

$$\text{if } z_{mt}=0 \Rightarrow \overline{\varrho}_{mtks} + \underline{\varrho}_{mtks} = 0 \Rightarrow T1=0, T2=0 \quad \forall m\in\mathcal{M}, t\in\mathcal{T}, k\in\mathcal{K}, s\in\mathcal{S} \tag{4.35a}$$

$$\text{if } z_{mt}=1 \Rightarrow \overline{\xi}_{mtks} + \underline{\xi}_{mtks} = 0 \Rightarrow T1=0, T2=0 \quad \forall m\in\mathcal{M}, t\in\mathcal{T}, k\in\mathcal{K}, s\in\mathcal{S} \tag{4.35b}$$

If z_{mt} is equal to zero then the Lagrangian multipliers $\overline{\varrho}_{mtks}$ and $\underline{\varrho}_{mtks}$ are equal to zero due to the complementary slackness condition, resulting in both expression T1 and T2 to be equal to zero. By analogy when z_{mt} is equal to one then $(1 - z_{mt})$ is equal to zero and using complimentary slackness conditions $\underline{\xi}_{mtks}$ and $\overline{\xi}_{mtks}$ are zero leading to T1 and T2 equal to zero.This property can be formulated mathematically through set of linearized disjunctive constraints:

$$-\Xi_m z_{mt} \leq \overline{\varrho}_{mtks} + \underline{\varrho}_{mtks} \leq \Xi_m z_{mt} \tag{4.36a}$$

$$-\Xi_m (1 - z_{mt}) \leq \overline{\xi}_{mtks} + \underline{\xi}_{mtks} \leq \Xi_m (1 - z_{mt}) \tag{4.36b}$$

Such reformulation will remove bilinear terms and will not affect the decision space. Similarly, the strong duality (4.26) of the problem (4.12) can be reformulated using (4.35) as in (4.37)

$$\begin{aligned}
&\sum_{t\in\mathcal{T}} \frac{\Psi}{(1+i_t)^{t-1}} \Big(\sum_{s\in\mathcal{S},k\in\mathcal{K}} \pi_s \big(\sum_{d\in\mathcal{D}} A_d d_{dtks} - \sum_{g\in\mathcal{G}} C_g \; g_{gtks} \big) - \\
&\sum_{e\in\mathcal{E}} \big(C_e^{(dh)} \tilde{d}_{etks} + C_e^{(ch)} \; \tilde{g}_{etks} \big) - \big(\sum_{e\in\mathcal{E}} C_{et}^{(E)} (e_{et} - e_{e(t-1)}) - \\
&\sum_{e\in\mathcal{E}} C_{et}^{(P)} (p_{et} - p_{e(t-1)}) - \sum_{w\in\mathcal{W}} C_{wt}^{(W)} (u_{wt} - u_{w(t-1)}) \Big) = \\
&\sum_{t\in\mathcal{T}} \Big(\sum_{d\in\mathcal{D}} D_d \overline{\omega}_{dtks} + \sum_{g\in\mathcal{G}} G_g \overline{\nu}_{gtks} + \sum_{w\in\mathcal{W}} \widehat{G}_w \varrho_{wtks} \overline{\kappa}_{ftks} + \\
&\sum_{e\in\mathcal{E}} \big(\widehat{P}_{et} \overline{\vartheta}_{etks} + \widehat{P}_{et} \overline{\kappa}_{etks} + \widehat{E}_{et} \overline{\rho}_{etks} \big) + \sum_{l\in\mathcal{L}} F_l \big(\underline{\sigma}_{ltks} + \overline{\sigma}_{ltks} \big) + \\
&\sum_{m\in\mathcal{M}} \widehat{F}_m \big(\overline{\gamma}_{mtks} + \underline{\gamma}_{mtks} \big) \Big)
\end{aligned} \tag{4.37a}$$

$$-\Xi_m z_{mt} \leq \overline{\varrho}_{mtks} + \underline{\varrho}_{mtks} \leq \Xi_m z_{mt} \quad \forall m\in\mathcal{M}, t\in\mathcal{T}, k\in\mathcal{K}, s\in\mathcal{S} \tag{4.37b}$$

$$-\Xi_m (1 - z_{mt}) \leq \overline{\xi}_{mtks} + \underline{\xi}_{mtks} \leq \Xi_m (1 - z_{mt}) \quad \forall m\in\mathcal{M}, t\in\mathcal{T}, k\in\mathcal{K}, s\in\mathcal{S} \tag{4.37c}$$

By doing algebraic reformulations described above the nonlinear problem (4.27) is transformed into a linear equivalent model which can be formulated as:

$$\begin{aligned}
&\underset{z_{mt}, y_{mt}, \Omega_s}{Maximize} \sum_{t \in \mathcal{T}} \langle \sum_{s \in \mathcal{S}} \pi_s (\sum_{l \in \mathcal{L}} F_l (\overline{\sigma}_{ltks} + \underline{\sigma}_{ltks}) + \\
&\sum_{m \in \mathcal{M}} \widehat{F}_m (\overline{\gamma}_{mtks} + \underline{\sigma}_{ltks}) + \Phi_t - P_t \sum_{m \in \mathcal{M}} C^{(T)}_{mt} y_{mt} \rangle && \text{(4.38a)} \\
&Subject\ to: \\
&z_{m,t=1} = 0 \ \forall m && \text{(4.38b)} \\
&z_{mt} = \sum_{\widehat{t} \leq t} y_{m,\widehat{t}} \forall m, \forall t \geq 2 && \text{(4.38c)} \\
&\sum_{t \in \mathcal{T}} y_{mt} \leq 1 \ \forall m, \forall t && \text{(4.38d)} \\
&\Phi_{t=1} = 0 && \text{(4.38e)} \\
&\Phi_t = \sum_{s \in \mathcal{S}} \pi_s \sum_{k \in \mathcal{K}} (\sum_{d \in \mathcal{D}} A_d d_{dtks} - \sum_{g \in \mathcal{G}} C_g g_{gtks} + \\
&\sum_{e \in \mathcal{E}} (C^{(ch)}_e \tilde{g}_{etks} + C^{(dh)}_e \tilde{d}_{etks}) - \sum_{l \in \mathcal{L}} F_l (\overline{\sigma}_{ltks} + \underline{\sigma}_{ltks}) - \\
&\sum_{m \in \mathcal{M}} \widehat{F}_m (\overline{\gamma}_{mtks} + \overline{\sigma}_{ltks})) - \sum_{s \in \mathcal{S}} \pi_s \sum_{k \in \mathcal{K}} (\sum_{d \in \mathcal{D}} (A_d d_{d(t-1)ks} - \\
&\sum_{g \in \mathcal{G}} C_g g_{g(t-1)ks}) + \sum_{e,k} (C^{(ch)}_e \tilde{g}_{e(t-1)ks} + C^{(dh)}_e \tilde{d}_{e(t-1)ks}) + \\
&P_t (\sum_{m \in \mathcal{M}} C^{(T)}_{mt} y_{m(t-1)} - \sum_{w \in \mathcal{W}} C^{(W)}_{wt} (u_{wt} - u_{w(t-1)}) - \\
&\sum_{e \in \mathcal{E}} C^{(E)}_{et} (e_{et} - e_{e(t-1)}) - \sum_{e \in \mathcal{E}} C^{(P)}_{et} (p_{et} - p_{e(t-1)})) \ \forall t \geq 2 && \text{(4.38f)} \\
&(4.24), (4.37) && \text{(4.38g)} \\
&(4.16), (4.2b) - (4.2l), (4.2o) - (4.2q) && \text{(4.38h)} \\
&(4.19), (4.10), (4.20) && \text{(4.38i)} \\
&\underline{\omega}_{dtks}, \overline{\omega}_{dtks}, \underline{\nu}_{gtks}, \overline{\nu}_{gtks}, \underline{\kappa}_{ftks}, \overline{\kappa}_{ftks}, \sigma_{ltks}, \\
&\overline{\xi}_{mtks}, \overline{\lambda}_{ntks}, \underline{\lambda}_{ntks} \geq 0 && \text{(4.38j)} \\
&z_{mt}, y_{mt} \in \{0, 1\} && \text{(4.38k)}
\end{aligned}$$

All four publications $J1$, $J2$, $J3$ and $J4$ attached to this thesis make use of the linearization and reformulation techniques presented in this chapter.

4.6 Decomposition techniques

Detailed investment planning problems presented in Section 4.1-Section 4.4 and later reformulated using techniques presented in Section 4.5 include a big range of parameters and variables. In addition, these problems include integer variables which are in fact a part of disjunctive constraints which model the investment decisions (to invest or not invest in particular asset). Presence of integer variables and disjunctive constraints makes aforementioned problems complex and computationally expensive. As a result, the solution process may take an extensive amount of time to provide the optimal result, moreover, in certain cases even commercially available solvers will fail to provide optimal results due to time limitations or limited memory capacity. Various decomposition techniques were proposed in the literature to tackle the problem of computational tractability of investment planning problems. Benders' decomposition by far is the most applied algorithm and it was proved to be effective on a big range of investment problems. However, Benders' decomposition has its limitations and can be less efficient when applied on problems with disjunctive parameters. In [86] Benders' based decomposition (further referred to as Beans' decomposition) was proposed as an attempt to remove the effect of disjunctive parameter. Beans' decomposition technique is based on Benders' decomposition algorithm where feasibility cut was modified and the effect of disjunctive parameter was removed. While this modification strengthen master problem of Beans' decomposition the subproblem still contains disjunctive parameter and may cause instabilities.

This section first briefly introduces theoretical background for disjunctive programs and for original Benders' decomposition applied on disjunctive problems. Benders' decomposition algorithm is then followed by original Beans' decomposition. Finally, the chapter contributes to the literature by providing a series of novel modifications and acceleration techniques applied on Beans' decomposition.

4.6.1 Disjunctive program

Disjunctive programming is a field in optimization theory where optimization (maximization or minimization)is performed on a problem which contains one or more disjunctive sets[4] [87]. Models (4.3) and (4.4) are two stage stochastic problems with first stage disjunctive constraints. Mathematically, the structure of a stochastic program with disjunctive constraints can be expressed in general mathematical form as:

---

[4] Disjunctive sets are also known as disjoint sets and can be described as sets which do not have any elements in common. In transmission expansion problem (4.3) disjunctive sets are introduced through power flow constraint of candidate lines (4.18)

$$\underset{x,\tilde{x}_s}{Minimize}\ \ cx + \mathbb{E}[d_s\tilde{x}_s] \tag{4.39a}$$

$$Subject\ to\ :$$

$$Ax + B\tilde{x}_s \leq b_s\ \ \forall s \in \mathcal{S} \tag{4.39b}$$

$$\vee_{i\in\mathcal{D}} \begin{bmatrix} Y_i \\ K_i x = p_i \end{bmatrix} \tag{4.39c}$$

$$Y_i \in \{True, False\}\ \ \forall i \in \mathcal{D} \tag{4.39d}$$

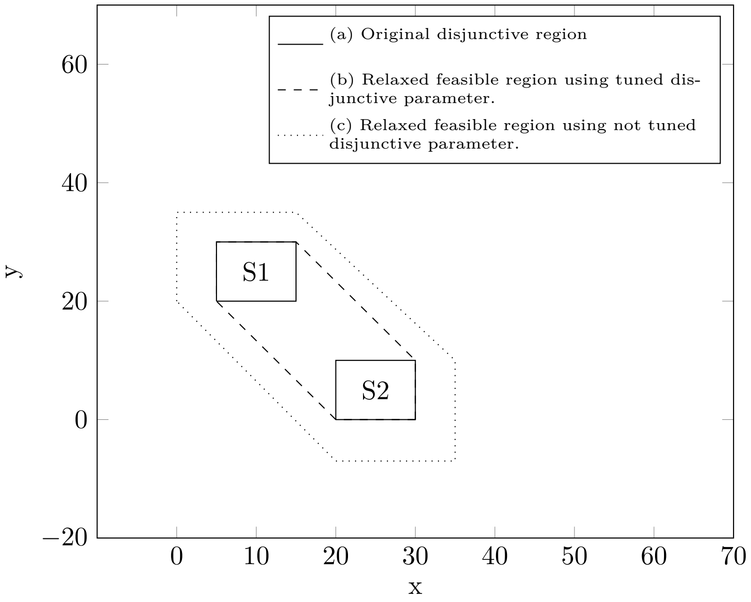
Constraints (4.39c) should hold if and only if corresponding logic condition Y_i is True. The logic condition Y_i in disjunctive problems is a variable and usually represented though integer variable. For example, in transmission investment decision problem logic condition Y_i is True (or equal to 1) if investment decision in line i is taken and False (or equal to 0) otherwise. At the same time if the investment decision in line i is taken power flow constraint constraints corresponding to line i should hold. This corresponds to disjunctive constraint (4.39c).

A disjunctive problem in its standard form can be relaxed using convexification techniques. A disjunctive program can be reformulated into a mixed-integer program using several existing techniques including convex hull, cutting planes and McCormick linearization. All these methods provide a reformulation of the original feasible sets and limitations specific for each method. Convex hull methods are proved to provide tight reformulation in a sense that the feasibility region of the reformulated problem will be as close as possible to the original feasibility region. Nevertheless, the approach requires additional variables and constraints which considerably increase the size of the problem and make it practically impossible to implement for large scale investment planning problems. On the other hand, the McCormick linearization does not affect the size of the problem. However, the disjunctive parameters involved in the reformulation create computational issues for the solver.

The impact of disjunctive parameter tuning on the relaxed feasible region is conceptually illustrated in Figure 4.2. $S1$ and $S2$ are original feasible regions with disjunctive property (either $S1$ or $S2$ is the feasible region). Relaxed feasible region using optimally tuned disjunctive parameters and the case when disjunctive parameter is not optimally tuned are demonstrated as region (b) and region (c), respectively. Consequently, region (b) is a tighter relaxation.

A disjunctive parameter that is not tuned affects the convergence of the problem [88]. The literature provides several methods to tune the disjunctive parameter. The methodologies for tuning disjunctive parameter can be found in [83] and [88]. The methods are proved to provide good approximations of the disjunctive parameters under certain conditions but additional large scale optimization problems should be solved for each case and the optimality still cannot be guaranteed. The problem of the disjunctive parameter tuning becomes especially hard when the reformulation involves variables without physical upper or lower limits which is the

Figure 4.2: The impact of disjunctive parameter tuning on the relaxed feasible region. Region corresponds to area inside dashed or solid lines.



case in the complementary slackness condition constraints or any other constraints which involve Lagrange multipliers.

4.6.2 McCormick linearization

McCormick linearization is used to linearize disjunctive linear sets and reformulate disjunctive program into mixed integer linear problem (MILP). A disjunctive program (4.39) reformulated using McCormick linearization can be mathematically expressed as:

$$\underset{x,\tilde{x}_s}{Minimize} \;\; cx + \mathbb{E}[d_s\tilde{x}_s] \tag{4.40a}$$

$$Subject\ to \; :$$

$$Ax + B\tilde{x}_s \leq b_s \;\; \forall s \in \mathcal{S} : (\mu_s) \tag{4.40b}$$

$$K_i x \leq p_i + (1 - y_i)H \;\; \forall i \in \mathcal{D} : (\overline{\sigma}_i) \tag{4.40c}$$

$$K_i x \geq p_i - (1 - y_i)H \;\; \forall i \in \mathcal{D} : (\underline{\sigma}_i) \tag{4.40d}$$

$$\sum_{i \in \mathcal{D}} y_i = 1 \tag{4.40e}$$

$$y_i \in \{0, 1\} \tag{4.40f}$$

The variables $\mu_s, \overline{\sigma}_i, \underline{\sigma}_i$ presented in the brackets and separated by colon are the corresponding Lagrange multipliers. The corresponding dual of the reformulated problem with fixed integer variables (4.40) is:

$$\underset{\tilde{x}_s}{Maximize} \sum_{s \in \mathcal{S}} b_s \mu_s + \sum_{i \in \mathcal{D}} (\overline{\sigma}_i (p_i + (1 - y_i)H) + \underline{\sigma}_i (p_i + (1 - y_i)H)) \tag{4.41a}$$

$$Subject\ to\ :$$

$$\sum_{s \in \mathcal{S}} A \mu_s + \sum_{i \in \mathcal{S}} K_i \overline{\sigma}_i + \sum_{i} K_i \underline{\sigma}_i \leq 0 \tag{4.41b}$$

$$B \mu_s \leq 0 \;\; \forall s \in \mathcal{S} \tag{4.41c}$$

$$\mu_s, \overline{\sigma}_i, \underline{\sigma}_i \geq 0 \; \forall s \in \mathcal{S}, i \in \mathcal{D} \tag{4.41d}$$

4.6.3 Benders' decomposition technique

The MILP model (4.40) has a special decomposable structure. Such structure allows us to decompose the problem into a number of independent optimization problems by separating the variables into two vectors. The first vector consists of continuous variables and the second one consists of integer variables. One of the decomposition methods for such types of problems is the Benders' decomposition [89]. Benders' decomposition algorithm is a widely used technique applied to reduce the computational burden of the problems with complicating variables, for example, such as integer variables. Various authors use a Benders' decomposition in investment decision problems in power systems. In [90] and [91], the Benders' decomposition is used to reduce computational time considering the uncertainty in the system. In [92], a modified version of the Benders' decomposition is applied on transmission investment game model and in [93], a modified Benders' algorithm is applied on bidding strategy optimization problem. In [94] and [95], modified Bender's decomposition is used to solve complex second-order cone problem. The Benders' decomposition proves to be an effective tool and helps to reduce the computational time substantially. In [90] the authors also apply Benders' decomposition technique without detailed discussion on the issues of tuning the disjunctive parameter and the disjunctive parameter is still present in the optimization and in the decomposition algorithm. In [96], additional Gomory cuts are introduced along with the traditional Benders' decomposition which allows one to approximate disjunctive parameter.

The Benders' decomposition algorithm includes two separate steps at each iteration. First, duality theory is used to determine upper bounds through fixing complicating integer variables (assuming a minimization program). The second step is to find a lower bound by solving the relaxed problem. The iteration between upper- and lower-bound programs is performed until the upper and lower bounds are close enough and the optimal solution is found. Accordingly, the Benders' decomposition simplifies the original MILP by splitting it into easier to solve

MILP and LP problems. In addition, such decomposition can be used on proposed MILP to remove the effect of the disjunctive parameter.

The standard Benders' decomposition algorithm applied to such types of problems includes a master problem (4.43) and a sub-problem (4.42) solved iteratively. The sub-problem at each decomposition iteration is formulated based on the dual of the original problem with fixed complicating variables. In the case of problem (4.40) the complicating variables are integer variables y_i. By fixing integer variables y_i as $y_i^{(a)}$ and counting it as a parameter the sub-problem can be formulated as the dual of the original problem with fixed integer variables described in (4.41). For clarity the formulation of the sub-problem is restated here:

$$\underset{\tilde{x}_s}{Maximize} \sum_{s \in \mathcal{S}} b_s \mu_s + \sum_{i \in \mathcal{D}} (\overline{\sigma}_i (p_i + (1 - y_i)H) + \underline{\sigma}_i (p_i + (1 - y_i)H)) \tag{4.42a}$$

$$Subject\ to\ :$$

$$\sum_{s \in \mathcal{S}} A\mu_s + \sum_{i \in \mathcal{D}} K_i \overline{\sigma}_i + \sum_{i \in \mathcal{D}} K_i \underline{\sigma}_i \leq 0 \tag{4.42b}$$

$$B\mu_s \leq 0 \ \ \forall s \in \mathcal{S} \tag{4.42c}$$

$$\mu_s, \overline{\sigma}_i, \underline{\sigma}_i \geq 0 \ \ \forall s \in \mathcal{S}, i \in \mathcal{D} \tag{4.42d}$$

The variables of the sub-problem μ_s, $\overline{\sigma}_i$ and $\underline{\sigma}_i$ are used as input parameters for $\mu_{s,a}^{(a)}$, $\overline{\sigma}_{i,a}^{(a)}$ and $\underline{\sigma}_{i,a}^{(a)}$ for the master problem. The master problem of Benders' decomposition applied on problem (4.40) can be formulated as:

$$\underset{z_a, y_i}{Maximize} \quad z_a \tag{4.43a}$$

$$Subject\ to :$$

$$z_a \leq \sum_{s \in \mathcal{S}} b_s \mu_{s,a}^{(a)} + \sum_{i \in \mathcal{D}} (\overline{\sigma}_{i,a}^{(a)} (p_i + (1 - y_i)H) + \underline{\sigma}_{i,a}^{(a)} (p_i + (1 - y_i)H)) \ \forall a \in \mathcal{G} \tag{4.43b}$$

$$\sum_{i \in \mathcal{D}} y_i = 1 \tag{4.43c}$$

$$y_i \in \{0, 1\} \ \ \forall i \in \mathcal{D} \tag{4.43d}$$

By solving the master problem (4.43) the values of the integer variables y_i are obtained. These values are used in the next iteration of the decomposition to update the parameters of the sub-problem ($y_i^{(a)}$). The standard Benders' decomposition algorithm is described in Algorithm 1

4.6.4 Beans' decomposition technique

Benders' decomposition presented in the previous section consists a master problem and sub-problem where both of them contain a disjunctive parameter H. As it was

Algorithm 1 Benders' decomposition algorithm

```
procedure BENDERS' DECOMPOSITION
    $y_i^{(a)}$ =initial feasible solution  UB=$\infty$; LB=$-\infty$
Solve sub-problem (4.42)
Update $\mu_{s,a}^{(a)}$, $\overline{\sigma}_{i,a}^{(a)}$ and $\underline{\sigma}_{i,a}^{(a)}$

    while UP-LB> $\epsilon$ do
        Append constraint (4.43$b$)
        Solve master problem (4.43)
        Update $y_i^{(a)}$
        Solve sub-problem (4.42)
        Update $\mu_{s,a}^{(a)}$, $\overline{\sigma}_{i,a}^{(a)}$ and $\underline{\sigma}_{i,a}^{(a)}$
    end while
    return Optimal solution $y_i$
end procedure
```

previously mentioned presence of disjunctive parameter can affect the computational tractability of the problem. Moreover, presence of the disjunctive parameter in the feasibility cut (4.43b) might also affect convergence to optimality of the whole algorithm. In order to avoid the effect of disjunctive parameter [86] proposes to reformulate the master problem of the Benders' technique into an equivalent set partitioning problem while the sub-problem remains the same. In this chapter the technique proposed in [86] is referred to as Beans' decomposition technique as the last name of the author of the publication. The master problem proposed in [86] is formulated as:

$$\underset{w_a, w_0, y_i}{Maximize} \sum_{a \in \mathcal{G}} P_a w_a + M w_0 \tag{4.44a}$$

$$Subject\ to\ :$$

$$\sum_{i \in \Omega_a^{(1)}} y_i + \sum_{i \in \Omega_a^{(2)}} (1 - y_i) \leq |\Omega_a^{(1)}| + |\Omega_a^{(2)}| - 1$$

$$+ \sum_{a' \Upsilon (P_{a'} \geq P_a)} w_a \ \forall a \in \mathcal{G} \tag{4.44b}$$

$$\sum_{a \in \mathcal{G}} w_a = 1 \tag{4.44c}$$

$$\sum_{i \in \mathcal{D}} y_i = 1 \tag{4.44d}$$

$$y_i \in \{0, 1\} \ \ \forall i \in \mathcal{D} \tag{4.44e}$$

Similar to Benders' decomposition the variables of the sub-problem are used to form feasibility cuts. However, unlike the Benders' decomposition the solution of the variables are not included directly in the cut but used to form new sets,$\Omega_a^{(1)}$ and $\Omega_a^{(2)}$. The solution of the variable is included in the set $\Omega_a^{(1)}$ or $\Omega_a^{(2)}$ if it is an extreme point. The sets $\Omega_a^{(1)}$ and $\Omega_a^{(2)}$ are used to represent index sets for extreme points corresponding to constraints with integer variables. The objective of the master problem is to select the best possible solution of the relaxed sub-problems, P_a. Input parameter P_a of the master problem is the objective function value of the sub-problem at each iteration a. The constraint (4.44b) represents feasibility cuts modeled according to the approach presented in [86]. Ancillary variables w_a are used to activate corresponding feasibility cut while w_0 is used to prevent unbounded solution, respectively. The solution of the master problem (4.44) is used as an input to the sub-problem (4.45). The sub-problem (4.45) is exactly the same as the sup-problem of Benders' decomposition (4.42) and restated here for clarity.

$$\underset{\tilde{x}_s}{Maximize} \sum_{s\in\mathcal{S}} b_s\mu_s + \sum_{i\in\mathcal{D}}(\overline{\sigma}_i(p_i+(1-y_i)H)+\underline{\sigma}_i(p_i-(1-y_i)H)) \tag{4.45a}$$

$$Subject\ to\ :$$

$$\sum_{s\in\mathcal{S}} A\mu_s + \sum_{i\in\mathcal{D}} K_i\overline{\sigma}_i + \sum_{i\in\mathcal{D}} K_i\underline{\sigma}_i \leq 0 \tag{4.45b}$$

$$B\mu_s \leq 0 \ \ \forall s \tag{4.45c}$$

$$\mu_s, \overline{\sigma}_i, \underline{\sigma}_i \geq 0 \ \ \forall i \in \mathcal{D}, s \in \mathcal{S} \tag{4.45d}$$

The decomposition procedure of the Beans' technique can be formulated as in Algorithm 2

Algorithm 2 Beans' decomposition algorithm

```
procedure BEANS' DECOMPOSITION
    $y_i$ =initial feasible solution  UB=$\infty$; LB=$-\infty$
Solve sub-problem (4.45)
Update $\Omega_a^{(1)}$ and $\Omega_a^{(2)}$
Set the maximum number of solutions in the solution pool
    while UP>LB do
        Append constraints (4.44$b$)
        Solve master problem (4.44)
        Update the value of fixed complicating variables $y_i^{(a)}$
        Solve sub-problem (4.45)
        Update $\Omega_a^{(1)}$ and $\Omega_a^{(2)}$
    end while
    return Optimal solution $y_i$
end procedure
```

4.6.5 Modified Beans' decomposition

The original Beans' decomposition presented in the previous section allows to avoid the effect of the disjunctive variable on the feasibility cut. However, the sub-problem (4.45) still contains the disjunctive parameters H which should be tuned to optimality. Such tuning is possible only for disjunctive parameters with known upper and lower limits. Thus, the presence of the disjunctive parameter in the sub-problem may still cause computational issues. In order to fully eliminate the effect of disjunctive parameter the following modifications are proposed. The proposed modifications are a part of the C4 contribution of this thesis.

The sub-problem (4.45) can be reformulated using Lemma 2 such that the disjunctive parameters are eliminated.

Lemma 2. If the disjunctive parameter H is tuned properly and optimization problem (4.45) is solved to optimality, then the objective function of (4.45):

$$\sum_s b_s\mu_s + \sum_i \overline{\sigma}_i(p_i + (1-y_i)H) + \underline{\sigma}_i(p_i - (1-y_i)H) \tag{4.46}$$

can be equivalently reformulated as a combination of a new objective function without disjunctive parameters and additional equality constraints:

$$\sum_s b_s\mu_s + \sum_i (\overline{\sigma}_i(p_i) + \underline{\sigma}_i(p_i)) \tag{4.47}$$

$$\overline{\sigma}_i((1-y_i)) = 0 \ \ \forall i \in \mathcal{D} \tag{4.48}$$

$$\underline{\sigma}_i((1-y_i)) = 0 \ \ \forall i \in \mathcal{D} \tag{4.49}$$

Proof. Assume that the disjunctive parameter H is tuned properly and optimization problem (4.45) can be solved to optimality. Then for the optimal solution to be reached the when the Karush-Kuhn-Tucker (KKT) conditions including the following complementary slackness conditions of the problem (4.40) are necessary to be satisfied:

$$\overline{\sigma}_i(K_i x - p_i + (1-y_i)H) = 0 \ \ \forall i \in \mathcal{D} \tag{4.50}$$

$$\underline{\sigma}_i(-K_i x - p_i + (1-y_i)H) = 0 \ \ \forall i \in \mathcal{D} \tag{4.51}$$

If y_i is equal to 0 then the constraints (4.40c) and (4.40d) are not active and the Lagrange multiplier $\overline{\sigma}_i$ and $\underline{\sigma}_i$ are strictly positive. Thus, the terms $\overline{\sigma}_i((1-y_i)H)$ and $\underline{\sigma}_i((1-y_i)H)$ are equal to 0. Similarly, if y_i is equal to 1 then the constraints (4.40c) and (4.40d) are active and the Lagrange multiplier $\overline{\sigma}_i$ and $\underline{\sigma}_i$ are equal to 0. Again, the terms $\overline{\sigma}_i((1-y_i)H)$ and $\underline{\sigma}_i((1-y_i)H)$ are equal to 0. Thus, the terms $\overline{\sigma}_i((1-y_i)H)$ and $\underline{\sigma}_i((1-y_i)H)$ are always equal to 0 if an optimal solution is reached. □

Using Lemma 2 the sub-problem (4.45) can be reformulated as:

$$\underset{\tilde{x}_s}{Maximize} \quad \sum_{s\in\mathcal{S}} b_s\mu_s + \sum_{i\in\mathcal{D}}(\overline{\sigma}_i p_i + \underline{\sigma}_i p_i) \tag{4.52a}$$

$$Subject\ to\ :$$

$$\sum_s A\mu_s + \sum_i K_i\overline{\sigma}_i + \sum_i K_i\underline{\sigma}_i \leq 0 \tag{4.52b}$$

$$B\mu_s \leq 0 \ \ \forall s \in \mathcal{S} \tag{4.52c}$$

$$\overline{\sigma}_i((1-y_i)) = 0 \ \ \forall i \in \mathcal{D} \tag{4.52d}$$

$$\underline{\sigma}_i((1-y_i)) = 0 \ \ \forall i \in \mathcal{D} \tag{4.52e}$$

$$\mu_s, \overline{\sigma}_i, \underline{\sigma}_i \geq 0 \ \ \forall s \in \mathcal{S}, i \in \mathcal{D} \tag{4.52f}$$

4.6.6 Accelerated modified Beans' decomposition

Authors in [97] propose a technique to strengthen Benders' feasibility cuts. A similar procedure can be applied on Modified Beans' decomposition. By applying cut strengthening technique computational tractability of the Modified Beans decomposition is improved and convergence time is accelerated. The aforementioned acceleration is a part of contribution C4 of this thesis.

The idea behind cut strengthening technique applied on Modified Beans decomposition is that the master problem of a decomposition algorithm in the early interactions may have multiple optimal solutions and, as a result, the steps between iterations might be too big. Too big steps between iteration may result in slower convergence rate. Thus, by analogy to technique presented in [97] in the early iterations additional constraint (4.53c) which limits the steps between iteration can be introduced. The master problem of Modified Beans' decomposition with additional constraint is formulated as:

$$\underset{w_a, w_0, y_i}{Maximize} \sum_{a\in\mathcal{G}} P_a w_a + M w_0 \tag{4.53a}$$

$$Subject\ to\ :$$

$$\begin{aligned}&\sum_{i\in\Omega_a^{(1)}} y_i + \sum_{i\in\Omega_a^{(2)}} (1-y_i) \leq |\Omega_a^{(1)}| + |\Omega_a^{(2)}| - 1\\ &+ \sum_{a\Upsilon(P_{a'}\geq P_a)} w_a \ \forall a \in \mathcal{G}\end{aligned} \tag{4.53b}$$

$$\sum_{i\Upsilon(y_i^a=1)} (1-y_i) + \sum_{i\Upsilon(y_i^a=0)} y_i \leq L_a \ \forall a \tag{4.53c}$$

$$\sum_a w_a = 1 \tag{4.53d}$$

$$\sum_{i\in\mathcal{D}} y_i = 1 \tag{4.53e}$$

$$y_i \in \{0,1\} \;\; \forall i \in \mathcal{D} \tag{4.53f}$$

The constraint (4.53c) greatly improves the convergence of the Modified Beans decomposition, however, the parameter L_a depends on the starting point and the iteration number and it is hard to identify. The parameter L_a should be manually tuned for each case study. Thus, in order to avoid such tuning we propose to penalize large steps at each iteration in the objective function using a penalty factor β_a. Penalty factor β_a does not need tuning and simply ensures that if master problem of the Modified Beans' decomposition technique has multiple optimal solutions the closest to the previous iteration will be chosen. The resulting Accelerated Modified Beans' master problem is formulated as.

$$\underset{w_a, w_0, y_i}{Maximize} \sum_{a \in \mathcal{G}} P_a w_a + M w_0 - \beta_a \Big(\sum_{i \Upsilon (y_i^a = 1)} (1 - y_i) + \sum_{i \Upsilon (y_i^a = 0)} y_i \Big) \tag{4.54a}$$

$$Subject\ to\ :$$

$$\sum_{i \in \Omega_a^{(1)}} y_i + \sum_{i \in \Omega_a^{(2)}} (1 - y_i) \leq |\Omega_a^{(1)}| + |\Omega_a^{(2)}| - 1$$

$$+ \sum_{a \Upsilon (P_{a'} \geq P_a)} w_a \;\forall a \in \mathcal{G} \tag{4.54b}$$

$$\sum_{a \in \mathcal{G}} w_a = 1 \tag{4.54c}$$

$$\sum_{i \in \mathcal{D}} y_i = 1 \tag{4.54d}$$

$$y_i \in \{0,1\} \;\; \forall i \in \mathcal{D} \tag{4.54e}$$

The proposed acceleration improves computational tractability of the master problem. On the other hand the master problem can be further accelerated using the parallel computing. The master problem during the initial iterations might have multiple optimal solutions. At each iteration, these multiple solutions are found and then the sub-problems associated to these optimal solutions are solved in parallel. The proposed accelerated algorithm is detailed in Algorithm 3 and illustrated in Fig. 4.3.

Algorithm 3 Accelerated decomposition algorithm

```
procedure SOLUTION ALGORITHM
    $y_i^{(a)}$ =initial feasible solution  UB=$\infty$; LB=$-\infty$
Solve sub-problem (4.52)
Update $\Omega_a^{(1)}$ and $\Omega_a^{(2)}$
Set the maximum number of solutions in the solution pool
    while UP>LB do
        Append constraints (4.54$b$)
        Solve master problem (4.54)
        Populate solution pool
        Solve sub-problems (4.52) in parallel for each element in the solution pool
        Update $\Omega_a^{(1)}$ and $\Omega_a^{(2)}$
    end while
    return Optimal solution $y_i$$
end procedure
```

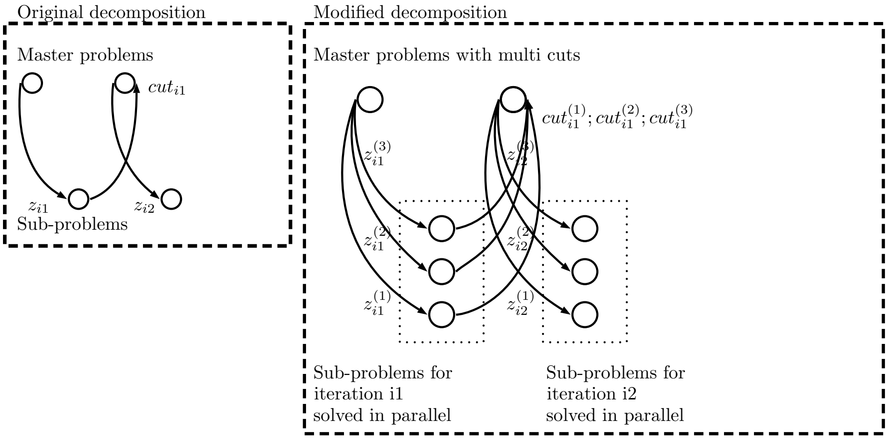


Figure 4.3: Accelerated Beans' decomposition algorithm

4.6.7 Performance

In order to test the performance of the Modified Beans' decomposition algorithm and Accelerated Beans' decomposition algorithm the transmission investment planning problem applied on IEEE 30-bus, 118-bus and 300-bus test systems is used. Data for the IEEE test systems are taken from data files of Matpower software, [98]. The additional data used for simulations can be found in Table 4.1. The performance of the Modified Beans' decomposition algorithm and Accelerated Beans'

Table 4.1: Input data for case studies.

	IEEE 30-bus	IEEE 118-bus	IEEE 300-bus
Number of candidate lines	20	30	60
Number of existing lines	30	175	411
Conventional Generation,(MWh)	335	4300	20678
Wind Generation, (MWh)	450	2500	12000
Scenarios, (N)	20	20	20
Operation subperiods, (N)	24	105	72
Maximum Load, (MWh)	600	4242	23526
Number of periods	10	10	15

Table 4.2: Results for IEEE 30-bus case study.

	Number of New Lines	Objective Function, ($)	Computation Time, (h)	Iterations
Without decomposition	4	145.15	0.485	-
Benders' decomposition algorithm	4	145.15	1.48	584
Modified Beans' algorithm	4	145.15	1.35	570
Accelerated Modified Beans' algorithm	4	145.15	0.456	152

decomposition algorithm is compared to the performance of the Standard Benders' decomposition algorithm and to the performance of the direct application of commercially available state-of-the-art CPLEX solver (without decomposition)[5]. All decomposition algorithms were implemented in GAMS software. The CPLEX solver is used to solve the MILP master problem and the sub-problem of each decomposition algorithm with the relative gap parameter set to zero. [6] The simulations are run on a computer with two processors and 128 GB of RAM.

---

[5] The disjunctive parameters included in the formulation which is solved by the CPLEX solver are tuned for relaxed problem (integer variables are fixed) using an iterative method where disjunctive parameters were increased till the point where the further change in the disjunctive parameters did not affect significantly the solution of the problem. It should be noted that we cannot guarantee that disjunctive parameters were tuned to optimality. We are not aware of any methodology which allows one to tune the disjunctive parameters without known upper bound to optimality.

[6] This setting can be relaxed to allow for a small relative gap for both Bean and Benders' decomposition algorithms. However, one should keep in mind that the strength of the cuts might be compromised. This is especially the case for Benders' decomposition algorithm.

Table 4.3: Results for IEEE 118-bus case study.

	Number of New Lines	Objective Function, ($)	Computation Time, (h)	iterations
Without decomposition	23	3859	24.5	-
Benders' decomposition algorithm	23	3859	31.9	7319
Modified Beans' algorithm	23	3859	10.15	5012
Accelerated Modified Beans' algorithm	23	3859	5.3	2510

Table 4.4: Results for IEEE 300-bus case study.

	Number of New Lines	Objective Function, ($)	Computation Time, (h)	iterations
Without decomposition	no solution after 100 hours of simulation			
Benders' decomposition algorithm	15	10159	89	44 000
Modified Beans' algorithm	15	10159	14.75	13 000
Accelerated Modified Beans' algorithm	15	10159	9.5	3192

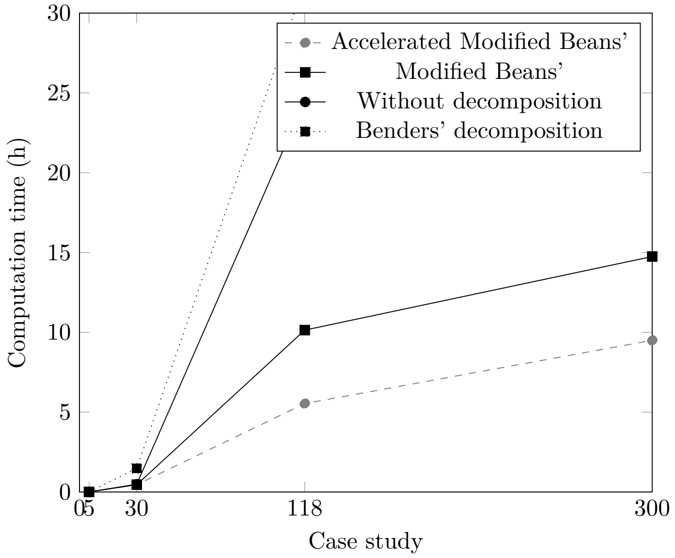


Figure 4.4: Comparison of computational time of different case studies.

The results show that both Modified and Accelerated Modified Beans' decomposition outperforms Standard Benders' Decomposition. The comparison of computational times of case studies is presented in Figure 4.4. Moreover proposed acceleration techniques allow further improve computational tractability of the decomposition and find an optimal solution in a reasonable time even for a large case studies such as IEEE 300-bus test system.

Publications $J3$ and $J4$ employ decomposition techniques presented in this chapter and provide numerical analysis.

Chapter 5

Conclusion and future work

The aim of this final chapter is to summarize main conclusions and outcomes of this dissertation as well as provide an outline of future research possibilities.

5.1 Summary

This thesis introduces mathematical models and solution methodologies which can be used to support investment planning in power systems. Proposed models are formulated to reflect the rising complexity of the investment decision process in power systems with growing share of renewable generation and corresponding need for flexibility sources.

This thesis started with the analysis of short-term planning of energy storage technologies and resulted in a conference paper C1. However, the literature review performed during the publication of the conference paper showed that short-term planning of energy storage is very close to hydro power planning and an extensive amount of literature on the subject was already present. One challenge not addressed in the literature was identified in optimal allocation and sizing of energy storage.

In order to cover that literature gap and analyze the investment planning problem of an energy storage owner under the competitive market rules a mathematical model was developed. The analysis showed that energy storage investments depend largely on transmission infrastructure. Under different system typologies energy storage and transmission lines can be seen either as substitutes[1] or complements[2]. In either case, in order for investments in energy storage to take place, there needs to be sufficient transmission network capacity.

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[1] Energy storage and transmission are considered to be substitutes when reduction in energy storage capacity results in symmetric revenue growth for transmission company and vice versa

[2] Energy storage and transmission are considered to be complements when reduction in energy storage capacity results in symmetric revenue decrease for transmission company and vice versa

Merchant investment planning fully depends on power prices which are more complex to simulate. Two different approaches can be used to simulate power prices and integrate them into merchant investment planning. The first approach is to generate various price scenarios and use them as input parameters when deciding on location and capacities. The second approach is to incorporate the market operation problem inside the investment planning problem. Both approaches result in large scale problems. The first approach requires a vast number of scenarios to cover the uncertainty range of future price development while the second approach requires a complex multilevel mathematical model which can be hard to solve. While both approaches are not ideal, the second approach where market operation is incorporated inside investment planning tends to provide a more accurate picture of the market operation and anticipate the effect of investment decisions on power prices. The integrated approach also allows to simulate coordinated investments including the effect of regulatory measures.

5.2 Concluding remarks

It can be concluded that adequate transmission capacity are prerequisite for energy storage investments. This is due to the relatively short life span of an energy storage, long contraction time of transmission lines and degradation of energy storage which will happen regardless if energy storage is under operation or not. Thus, energy storage is most likely to follow a transmission investment decision and not vice versa. A similar logic can be applied to wind investment decisions. While energy storage and generation companies follow competitive market laws, transmission companies are highly regulated and can be characterized as natural monopolies. Without proper regulation such regulatory segregation results in limited information exchange between transmission companies and other utilities such as generation or energy storage companies. Consequently, transmission companies are unable to anticipate or forecast the future development of independently owned utilities and therefore to perform investment planning. This results in a situation when transmission investment is performed only after the investment planning of independently owned utilities is finalized. Thus, a contradiction arises where independent utilities can not invest due to limited transmission and transmission companies do not invest due to limited development in generation and energy storage. As a result, a stagnation in power system development appears. In order to avoid stagnation the investment planning in transmission, generation, and energy storage assets should be performed in a coordinated manner. In a deregulated economy coordinated investment planning is problematic due to competitive driving forces and limited information exchange.

One solution may be a regulatory entity that can support efficient development of the power sector by coordinating investment planning of different utilities and transmission companies. This coordination can be achieved by providing various incentive mechanisms for investment planning when price signals are not sufficient.

Incentive mechanisms are especially relevant for transmission investments where price signals cannot cover high capital costs of transmission lines. The analysis provided in this thesis as well as in publications J2-J4 show that, in particular, H-R-G-V and ISS incentive mechanisms are efficient and provide social welfare maximizing outcome. Moreover, the application of H-R-G-V and ISS invective mechanisms results in proactive transmission investments. Numerical studies and simulations on transmission planning support the analytical argument that unregulated transmission planning may result in under investment while Cost-Plus incentive mechanism may result in over investment.

The analysis of regulated investment planning also supports the conclusion that transmission investments are prerequisite for investments in energy storage and wind generation. Timely and efficient transmission expansion results in social welfare maximizing investments in energy storage and wind generation (as it was shown in the case studies provided in J2 and J4).

Incentive mechanism and regulatory measures can be integrated into investment planning by modeling decision making of a regulatory entity or by directly integrating incentive mechanism (or a regulatory measure) through regulatory constraints. Either approach complicates mathematical models used to simulate investment planning in power systems. If an investment planning problem is simulated considering a large power system, such as IEEE 300 node test system, the corresponding problem can become intractable and commercially available solvers will not be able to provide an optimal solution. (One such example where an investment problem becomes intractable is provided in publication J3.)

In some cases, a complex and large scale model can be efficiently relaxed to its simplified equivalent and decomposed into a series of smaller problems. In Chapter 4 of this thesis, a reformulation methodology consisting of a series of algebraic transformations and relaxations is used to convert a bilevel, nonlinear problem into a one-level linear equivalent problem with a decomposable structure. The obtained structure is then used to design a tailored decomposition algorithm which allows to improve the computational tractability of the problem. The reformulation methodology and decomposition technique depends on the initial structure of the model, and can be easily modified to adapt small changes in the model design. Moreover, regardless of the technology, most of the investment planning problems in power systems can be simulated using models provided in this thesis and consequently the reformulation methodology and decomposition techniques can be applied on these models as well. The proposed reformulation methodology and decomposition techniques can be used to support investment planning processes in various power system utilities as well as to support the decision making of a regulatory utility.

5.3 Open questions and future work

Investment models and solution methodologies provided in this thesis can be used to gain valuable insights into the future developments of power systems and to support investment planning processes. However, the presented investment models use several assumptions which may limit the analysis such as:

- The models assume perfect information and perfect competition to simulate market operation. While most of the electricity markets aim to achieve perfect information and perfect competition, in practise utilities can withhold crucial information to manipulate the market.
- The performance of assets such as energy storage in electricity markets depends largely on its bidding strategy. In this thesis, the bidding strategy is not considered when the revenue stream is computed.
- The main revenue stream of generators and energy storage is assumed to come from energy only markets and is based on spot prices.
- The models use representative days in order to simulate long-term planning. Representative days are chosen as average (representative) days for each season. While the logic behind such selection methodology has been widely used in the literature, the accuracy of the methodology was not validated.
- The decomposition techniques presented in this thesis assume that integer variables are present in the upper-level only and are not applicable for models with integer variables on the lower level.

In order to have a deeper understanding of investment planning problems and regulatory frameworks the aforementioned assumptions can be changed and the following improvements can be performed.

- Market clearance and the operation of each asset such as energy storage, generator, or load can be formulated as decoupled models. The asset operation models will then require modeling of the bidding strategy under the profit maximizing objective.
- Market operation can be extended to include joint clearing of a combination of multiple markets such as spot market and balancing markets as well as ancillary services to the system (e.g., frequency regulation, reserves).
- A methodology to select representative days can be developed so the minimum number of representative days is used and the accuracy of the revenue stream estimation is not compromised.
- Bean's decomposition technique can be extended for the general bilevel problem decomposition by utilizing disjunctive properties of the lower-level problem.

Some of these open questions and future work suggestions were partially addressed during the PhD study and resulted in several paper drafts which are in prepapration to be submitted to peer-reviewed publications in the near future.

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List of publications

Published and accepted journal articles in journals listed in Journal Citation Report (JCR):

- *J1*: Khastieva, D., Dimoulkas, I., and Amelin, M., ”Optimal Investment Planning of Bulk Energy Storage Systems,” *Sustainability*, 10(3), 610, 2018.
- *J2*: Khastieva, D, Hesamzadeh, M. R., Vogelsang, I., Rosellón, J., and Amelin, M., ”Value of energy storage for transmission investments,” *Energy Strategy Reviews*, 24, 94-110, 2019
- *J3*: Khastieva, D., Hesamzadeh, M. R., Vogelsang, I., and Rosellón, J., ”Transmission Network Investment Using Incentive Regulation: A Disjunctive Programming Approach,” *Networks and Spatial Economics* - Springer (Accepted)

Submitted article in journal listed in JCR:

- *J4*: Khastieva, D., Mohammadi S., Hesamzadeh, M. R., Bunn D., ”Optimal Transmission Investment with Regulated Incentives based upon Forward Considerations of Firm and Intermittent Resources with Batteries” *IEEE Transactions on Power Systems*

Peer-reviewed articles published in proceeding of conferences:

- *P1* Khastieva, D., and Amelin, M. (2016, July), ”Short-term planning of hydro-thermal system with high wind energy penetration and energy storage,” in IEEE Power and Energy Society General Meeting (pp. 1-5), IEEE, 2016.

Curriculum vitae

Dina Khastieva

Work Experience

Current-
Mar 2019
Quantitative Risk Analyst at Vattenfall AB, Stockholm, Sweden
Department: Corporate Stuff Functioning
Quantitative analysis of investment projects in energy sector and investment model reviews.

Current-
Oct 2014
PhD at KTH, Royal Institute of Technology, Stockholm, Sweden
Department of Electric Power and Energy Systems

Research: In my research I concentrate on electricity markets, operation and planning of energy storage technologies and transmission investment planning. In my work I focus on mathematical modeling approach which includes hard-to-solve mathematical problems and various solution and optimization techniques. My research combines optimization, mathematics, economics, data science and programming. The outcome of my work was presented in several published papers and more are currently under revision.

Teaching: During my PhD studies I was involved in course planning and lecturing for master level courses. I planned and gave lectures on stochastic short-term operation for Power Generation, Environment and Markets course. I gave lectures on short-term planning and mathematical modeling for Power Generation Operation and Planning course.

Sep 2016-
Jun 2017
Visiting researcher at Pontifical Comillas University, Madrid, Spain
Institute for Research in Technology
Developed mathematical models for energy storage operation and planning under various balancing and reserve markets

Education

May 2014
Graduate Degree (Master of Science) in Systems and Control Engineering,
Case Western Reserve University, Cleveland, OH, USA
Thesis: "Energy Storage Impact on Systems with High Share of Wind"
Gpa: 3.83/4

Jul. 2012
Undergraduate Degree (Specialist Diploma) in Economics and Mathematics
Mathematical methods in economics, Faculty of Computer Science and Cybernetics
Kazan Federal University, Kazan, Russia
Gpa: 4.75/5

Scholarships and Certificates

Feb. 2018
Winner of the Hackathon organized by SaltX
Funding to develop a project concerning application of thermal storage to commercial and residential saunas.

Jun. 2014
Erasmus Mundus scholarship for graduate studies
SETS program

Jul. 2012
Scholarship for graduate studies with an outstanding curriculum
Finalist in "Algarish" program, Tatarstan, Russia

Languages

Russian: Mother tongue
Tatar: Mother tongue
English: Fluent
Spanish: Basic knowledge
Swedish: Basic knowledge

Computer Skills

GAMS, Julia, Matpower, Matlab, C++, C#, Python, Octave, SQL, Visual

Interests

Electricity markets, Optimization techniques, Programming, Decision making, Machine learning, Statistical Analysis