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Impact of actor behaviour on the circular debt crisis in Pakistan's electricity sector
– An Agent-Based Modelling approach

IMPACT OF ACTOR BEHAVIOUR ON THE CIRCULAR DEBT CRISIS IN PAKISTAN'S ELECTRICITY SECTOR

An agent-based investment model of the electricity sector of Pakistan to explore the influence of investors investment strategy and the market regulator's price-setting strategy on circular debt

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MASTER OF SCIENCE
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By

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EXECUTIVE SUMMARY

A reliable, accessible, and affordable electricity provision is crucial for economic development in emerging markets. It is the lifeblood of almost all processes in a country. A small business needs electricity for their machines to work and large industrial processes require continuous power. Also, education and security depend on electricity for essential facilities such as (street)lighting. The stakes are high not only for businesses and consumers: a large set of stakeholders related to the transmission and distribution of electricity relies on the sector for their revenues and livelihoods.

For some emerging countries, ill-advised policies, unfortunate market development, and a bad starting position together with the already complex nature of the electricity sector caused circular debt to accumulate. *Circular debt is a self-reinforcing shortfall of revenue throughout the value chain that tends to look like a "vicious circle" without a proper solution.*

One of the root causes of circular debt is expensive and inefficient electricity generation. The expectation is that an increase in renewable energy will reduce the price of electricity due to the low production costs and consequently reduce circular debt. The additional benefit of Variable Renewable Energy (VRE) integration is the reduced reliance and exposure to fossil fuel imports and crude price fluctuations. In a single buyer market structure, renewable energy investments depend on *the price-setting behaviour of the market regulator* and *the investment strategy of investors*. However, the effect of these actors' investment decisions and price settings strategies on circular debt remain largely unclear.

Studies performed in wholesale markets of OECD countries point out that applying complex adaptive thinking is a valuable approach to explore the development of the electricity market. It is, however, unknown how to apply complex system thinking to single buyer markets in emerging countries. More specifically, (1) it is unknown how to model the potential pathways of the electricity price, (2) how to integrate decision-making by investors and market regulators in an investment model and, (3) how to causally link the development of the electricity market price to circular debt. Therefore, the research revolves around the main research question, which reads as follows:

How will different investment decisions and price settings strategies, within the energy transition context, effect circular debt?

This study follows two main steps: (i) an agent-based investment model is used to link actor behaviour to contracted market prices and VRE share, (ii) a qualitative analysis links the model results to the development of circular debt. This study is focused on the electricity sector and the current circular debt crisis in Pakistan.

First, the agent-based investment model explores the impact of price-setting strategies of the market regulator and investment decisions of investors on two key performance indicators (a) the contracted market price and (b) the shares of variable renewable energy types in the total energy mix in Pakistan. Three types of private investors in generation capacity are distinguished: Development Banks, progressive and conservative investors. They act according to the Diffusion of Innovation Theory as front runners or followers in the energy transition. The market regulator NEPRA can show a progressive or conservation attitude towards renewable energy. Table 1 presents the four behavioural scenarios which are tested in the Agent-Based Investment Model during a 25-year transition.

Table 1: 2x2 matrix shows the behavioural scenarios of market regulators and investors resulting in four scenarios (A, B, C, D). The vertical axis shows the price-setting behaviour of the market regulator: progressive or conservative

regarding VRE generation. The horizontal axis shows the attitude of investors: followers or front runners in the energy transition.

		Investor's attitude	
		Followers	Front runner
Market regulator renewable energy price-setting	Progressive	A	B
	Conservative	C	D

Second, the contracted electricity market price is linked to circular debt using historical observations of two previous circular debt crises in Pakistan and an analysis of the current challenges that drive circular debt.

The results of the agent-based investment model show a decreasing electricity price in all scenarios. The most considerable price reduction can be observed in the scenarios where investment decisions and price-setting strategies favour VRE investments (progressive market regulator and front runner investment attitude). Furthermore, the market regulator's price-setting strategy has a more significant influence on the electricity price than investors' investment attitude. If the market regulator's attitude is progressive, the share of VRE increases from 5% in 2020 to a majority share (70-80%) in 2045, and the contracted market price reduces from US$83 to a tariff between US$ 45 and 50. When the market regulator's attitude is conservative, the share of VRE increases from 5% in 2020 to a minority share (25% - 35%) in 2045, and the contracted market price reduces from US$83 to a tariff between US$ 60 and 65.

Literature and expert interviews show that the current direction of the Pakistani market regulator leans towards a conservative price-setting. This direction is hard to change as the electricity systems draw on a path-dependent nature. However, this could change due to the urgency of the energy transition and the circular debt crisis.

In addition, this study's qualitative research confirms the *positive causal relationship* between contracted market prices and circular debt of previous studies. However, no conclusions can be drawn about the *degree of causality* between lower contracted market prices and an improved circular debt position. The savings resulting from the lower generation tariffs in Pakistan can be redistributed in multiple ways: lower consumer prices, reduced sovereign debt, or reduced circular debt by increasing subsidy payments to the distribution companies.

The analysis also shows a mismatch between the short-term problem of circular debt and the long-term solution of integrating renewable energy. Integration of VRE is not a solution for the current circular debt crisis but a vital long-term driver to prevent the repetition of circular debt crises. It is nevertheless essential to invest in VRE projects in the short term to create success stories that influence the attitude of the market regulator and investors. A behaviour change paves the way for large-scale renewable energy integration that sustain the long-term prevention of new circular debt crises.

This study makes four specific recommendations to stakeholders in the Pakistani electricity sector that accelerate VRE investments and therefore reduce the risk of new circular debt crises in the long term. The focus is not so much on the technical feasibility of renewable energy, but on feasible behavioural changes of the various stakeholders within the political context of the circular debt crisis. (1) The Dutch Development Bank FMO, active in Pakistan's energy sector, is recommended to support and finance VRE generation capacity, transmission grid improvements, and electricity storage in order to create success stories. (2) Furthermore, the government of Pakistan should consider shortening and smoothing the pre-investment period of VRE projects in order to attract more investors. (3) Third, the Pakistani market regulator NEPRA could increase VRE projects by allowing project developers[1] to propose new VRE sites alongside the market regulator. (4) Finally, NEPRA is recommended to shift their focus in power purchase agreements of new thermal powerplants from baseload capacity to flexible capacity. This step is essential to anticipate on the variability of renewable sources.

From a scientific point of view, this study contributes by proposing an agent-based investment model that explores the future states of the electricity sector of Pakistan in the context of the energy transition. It shows the possibility to model a single buyer electricity market from a complex adaptive socio-technical viewpoint. Thereby, this study extends the application of agent-based models in wholesale markets in OECD countries to single buyer markets in emerging countries. Furthermore, the research presents a new method to conceptualise investors' and market regulator's behaviour assuming heterogeneity of actor behaviour and bounded rational decision-making. Finally, this study adds to the existing knowledge by linking investment decisions and price-setting strategies to circular debt through the combination of quantitative agent-based model results with qualitative research.

[1] A project developer is the entity leading and in charge of building the new generation capacity. Investors are typically banks that finance the project developer's electricity generation project.

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LIST OF ABBREVIATIONS

ABM	Agent-Based Modelling
ADB	Asian Development Bank
AEDB	Alternative Energy Development Board
CPPA	Central Power Purchasing Agency
CRT	Cost Recovery Tariff
DFI	Development Finance Institute
DISCO	Distribution Company
FIT	Feed-In-Tariff
FMO	Dutch Entrepreneurial Development Bank
GENCO	Public Generation company
GoP	Government of Pakistan
IFC	International Finance Corporation
IMF	International Monetary Fund
IPP	Independent Power Producer
KE	K-Electric
LCOE	Levelised Cost of Electricity
NEPRA	National Electric Power Regulatory Authority
NTDC	National Transmission and Despatch Company
OECD	Organisation for Economic Co-operation and Development
PAEC	Pakistan Atomic Energy Commission
PEPCO	Pakistan Electric Power Company
PLAC	Partial Load Adjustment Charges
PPA	Power Purchase Agreement
PPIB	Private Power and Infrastructure Board
PTI	Pakistan Tehreek-e-Insaf
SDG	Sustainable Development Goal
SPP/CPP	Small Power Plants / Captive Power Plants
T&D	Transmission and Distribution
TDS	Tariff Differential Subsidy
WAPDA	Water and Power Development Authority
WB	The World Bank
ROI	Return-On-Investment

LIST OF FIGURES

1. INTRODUCTION

1.1. Debt burden is a problem many energy markets in emerging countries face

A reliable, accessible, and affordable electricity provision is crucial for economic development in emerging markets (Course reader, SEN1522 Electricity and Gas, CoSEM master, TU Delft, 2019, p7; Sarkodie and Adams, 2020). It is the lifeblood for almost all processes in a country (Sarkodie and Adams, 2020). A small business needs electricity for their machines to work and large industrial processes require continues power. Also, education and security depend on electricity for essential facilities such as (street)lighting. The stakes are high not only for businesses and consumers: a large set of stakeholders related to the transmission and distribution of electricity relies on the sector for their revenues and livelihoods.

Therefore, it is no surprise that the functioning of a country's electricity system is politically sensitive, with many conflicting interests. For some emerging countries[2], ill-advised policies, unfortunate market development, and a bad starting position together with the already complex nature of the electricity sector caused circular debt to accumulate (Bacon 2019, 14; World Bank 2020, 20; van Dam et al. 2019, 2). *Circular debt is a self-reinforcing shortfall of revenue throughout the value chain that tends to look like a "vicious circle" without a proper solution.*

The development of circular debt starts with Distribution Companies (DISCO) accumulating debt. Those entities function as middlemen who buy electricity from a state-owned monopolist (called "the single buyer") and sell it to consumers, see Figure 1 (Heller and Victor, 2004). Debt accumulation by DISCOs is the result of a mismatch between the revenues needed for full-cost recovery and the actual revenues realized by DISCOs.

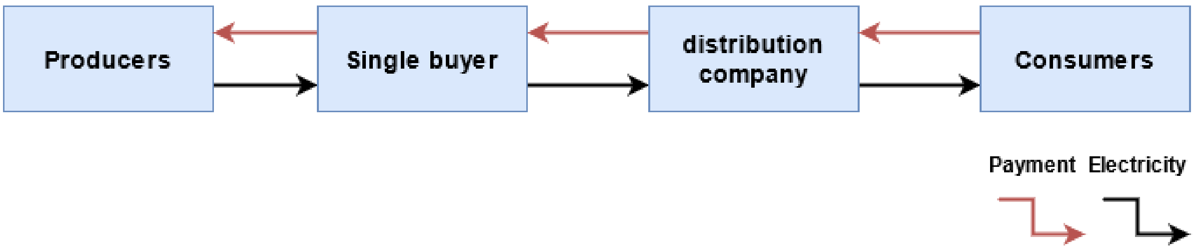

Figure 1: The single buyer market structure. The red arrow is the stream of payments. The black arrow is the order of electricity transmission.

The lack of revenues occurs because DISCOs sell electricity for a consumer tariff restricted by the government (World Bank 2020, 16). To prevent public unrest and gain popularity, some governments set the end-user tariff lower than necessary for full-cost recovery. When revenues from electricity sales are lower than the necessary revenues to offset all costs, a DISCO operates under cost-recovery levels. In this case, the central government has two options: (1) the government fills the gap with subsidies or (2) DISCOs accumulate debt. In the former option, the government's deficit increase. In the latter case, DISCOs are forced to adopt a range of suboptimal strategies to deal with a lack of revenues (World Bank 2020, 19). Such strategies include high-cost, short-term commercial debt, and informal borrowing in the form of payment arrears to various electricity generators and raw fuel suppliers (World Bank 2020, 19). When DISCOs' debt accumulate is left untreated for a long-time, debt spread to other actors in the value chain, which results in circular debt. Figure 2 illustrates the decisions made in the system that either cause public deficit, public utility debt, or circular debt.

[2] Other countries facing/faced circular debt: Ghana, Zambia, Honduras, and Haiti

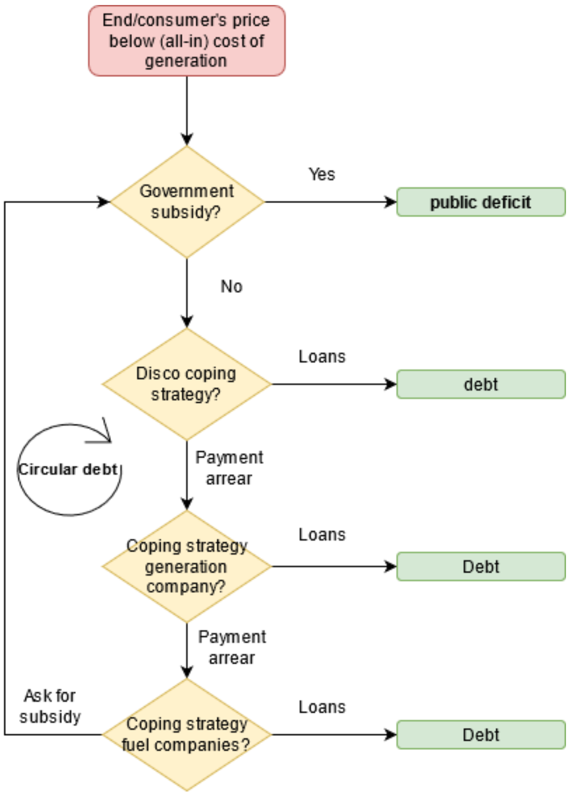

Figure 2: Decision tree in single buyer market with end-user tariffs lower than necessary for full cost recovery. The illustration shows various places of debt accumulation in the electricity system. Yellow diamonds are decision nodes, green rectangles are places of fiscal debt, and red is the starting condition.

Circular debt is formed over decades and is rooted in a complex web of technology, (geo)politics, market design, economics, and path dependence. Therefore, an easy solution is not readily available. From all the barriers solving circular debt, the most apparent problem is the political stalemate of electoral pressure to keep consumer prices down and vested interest hindering (unfavourable) sector reforms (World Bank 2020, 5; IMF 2006, 20). Historically, the remedy for circular debt was increased consumer prices and reforms based on the standard textbook electricity model of unbundling, privatization, maximum competition, and introduction of an independent regulator to oversee the monopoly-prone parts of the system (Heller and Victor, 2004). The World Bank and the IMF followed this line of reasoning for almost thirty years. The approach even received a nickname: 'The Washington Consensus'. However, in a recent report, the World Bank (2020) reflected on this policy and concluded that this approach was in many cases unsuccessful.

In the same report, the World Bank concluded that increasing the cost-efficiency of the system did work for emerging countries (World Bank, 2020). Over the 25-years under reflection, the focus regarding cost-efficiency was mainly on reducing system losses in the transmission system (World Bank, 2020, 19). However, with the energy transition kicking in high gear, helped by the astonishing cost decline of renewable energy, there is a new set of possibilities to increase cost-efficiency of the system (Valasai, 2017; Kraan et al., 2018). Renewable energy is a game-changer that influence all aspects of a country's energy supply, ranging from high-level geopolitics and climate change to national infrastructure topology and market operations to local level decentral generation and business case opportunities (Scholten et al. 2018, 5). Therefore, the context in which solutions for circular debt are viewed should be adapted to the new reality that renewable energy inevitable brings.

For new cost-efficient power generation plant (foreign) investments by the private sector are essential (Sarkodie, 2019). For private investors, an investment is only worthwhile when there is a positive business case. In emerging markets, this business case is primarily determined by the market regulator which offers some form of cost-plus tariff[3] for new generation capacity. The determination of the cost-plus tariff comes about with at least significant governmental influence (World Bank 2020, 17). Therefore, in a single buyer market design the perspective of investors is shaped by the behaviour of the single buyer. This is in contrast with OECD countries[4] where investors primarily decide on an investment based on their long-term estimation of the prices on the wholesale market (Course reader, SEN1522 Electricity and Gas, CoSEM master, TU Delft, 2019, p43).

The expectation is that an increased share of variable renewable energy will reduce the price of electricity due to low-cost electricity production and consequently reduce circular debt (Zameer et al., 2018). The additional benefit is that the reliance and exposure to fossil fuel imports and price fluctuation decline with variable renewable energy integration (Zameer et al., 2018). In a single buyer market structure, the extent to which renewable energy investments are made depends on the market regulator's price-setting behaviour and investors' investment decisions. However, the effect of different behaviour on the circular debt remains largely unclear. Table 2 presents a conceptual view of what is meant with different behavioural types of investors and market regulators.

Table 2: 2x2 matrix shows the behavioural scenarios of market regulators and investors resulting in four scenarios (A, B, C, D). The vertical axis shows the price-setting behaviour of the market regulator: progressive or conservative regarding variable renewable energy generation. The horizontal axis shows the attitude of investors: followers or front runners in the energy transition.

		Investor's attitude	
		Followers	Front runner
Market regulator renewable energy price-setting	Progressive	A	B
	Conservative	C	D

A market regulator can either be progressive, which means it supports a quick uptake of Variable Renewable Energy (VRE) by offering an attractive production tariff for new VRE projects, the regulator can be conservative, resulting in an emphasis on fossil fuel and, therefore, offering a less attractive production tariff for VRE projects. The investors can be followers, which means they are sceptical about embracing VRE or a front runner that embraces VRE. Modelling provides insight into the effect of actor behaviour on circular debt by exploring the four scenarios depicted in Table 2.

In sum, investments in new generation capacity, and therefore the future energy mix, is shaped by the market regulator and investors interacting in the new context of the energy transition. For emerging markets burdened with circular debt, a step forward to a more cost-effective generation mix start with a better understanding of the effect of different strategies by a market regulator and investors on the future costs and the generation mix of electricity.

1.2. Knowledge gaps

It is acknowledged by researchers to view, model and research the electricity system as a complex adaptive socio-technical system (van Dam et al., 2013). In this complex adaptive system thinking,

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[3] Producers revenue per kWh

[4] OECD stands for countries who are member of the Organisation for Economic Co-operation and Development. This is an intergovernmental economic organisation with 38 member countries. Generally, the OECD members are high-income economies.

the behaviour of actors and interaction among actors is a starting point for understanding (long-term) emergent system-level behaviour. However, researchers or institutions studying circular debt have not applied the complex adaptive thinking to study the circular debt crisis. Currently, it becomes more relevant to research circular debt in the context of the energy transition and the rapid cost reduction of renewable energy because it adds a new palette of solutions. This paragraph touch upon the four themes of the literature review, and the remainder of the section identifies three knowledge gaps that this research aims to fill.

First, the energy transition will influence the production price of electricity of countries facing circular debt (The World Bank, 2020a). The future production price of electricity is currently only researched using optimisation models (The World Bank, 2020b; National Transmission and Dispatch Company, 2020). It is not yet researched, qualitatively or quantitatively, using a complex adaptive socio-technical viewpoint. Therefore, the aim of this research to fill the void of understanding the potential development of the production price of electricity during the energy transition using a complex adaptive socio-technical system approach.

Second, by adopting the complex adaptive viewpoint, decision making and actor interaction becomes a key part of understanding how the energy transition will impact circular debt. In the current body of literature, a conceptualisation of decision-making by key players in single-buyer electricity market is not present.

Third, in the field of complex systems, it is common to use agent-based models to explore possible future states of a system (van Dam et al., 2013). Such models, especially for large-scale systems such as the electricity system, are a low detail abstraction of reality. However, circular debt is a broad challenge where many (sub) systems and associated factors play a role. Gaining more profound insight into circular debt would benefit from combining abstract quantitative insights from an agent-based model with a qualitative view on circular debt. In literature, it is ill-understood how to link quantitative data on electricity prices to qualitative insight on circular debt development.

Finally, the cost of VRE is included as Levelized Cost Of Electricity (LCOE), neglecting the cost of intermittency (Joskow., 2011; Ueckerdt et al., 2013; IEA, 2020). Recently, the first data are brought together that indicates these costs (Hepstonstall and Gross, 2021). However, the influence of these additional integration costs on the potential of renewable energy to mitigate circular debt is not yet researched.

Identified knowledge gaps

1. It is ill-understood what the potential pathways are of the production price of electricity during the energy transition using a complex adaptive socio-technical system approach
2. It is unclear how to integrate decision-making by investors and market regulators in a single-buyer investment model.
3. It is yet to be researched how to link the quantitative results on market prices to the development of circular debt
4. It is unclear what the implications are of including integration cost of variable renewable energy on the mitigation of circular debt

1.3. Research objective and research questions

This research aims to provide insight into the effect of actor behaviour on circular debt in the context of the energy transition. An additional objective is to increase the understanding of circular debt from a complex adaptive viewpoint. To this end, a modelling approach simulating investment behaviour in the electricity market of Pakistan is developed. There are already several other agent-based model studies performed that look at electricity markets focussing on the energy transition and investors behaviour (Kraan et al., 2018). However, the application on emerging markets with a different market structure combined with circular debt is a novel terrain for agent-based studies. The goal of the model is to capture the fundamental states, behaviour, and interaction of investors and market regulators in an agent-based model to explore possible pathways influencing circular debt in the energy transition context. Results from this study are expected to give additional insights on how to mitigate circular going forward.

1.3.1. Main research question

This research is centred around one main research question that aims to answer the identified knowledge gaps. The main research question is demarcated by the research scope and motivated by the research objective. The following research question is posed for this thesis:

How will different investment decisions and prices settings strategies, within the energy transition context, effect circular debt?

The main research question assumes that investors' investment decisions and the market regulator's price-setting strategy influence new investments in generation capacity.

1.3.2. Sub-questions

In this paragraph, the main research question is divided into four sub-questions. Each sub-question will separately be discussed.

Sub-question 1: What are the foremost causal drivers and interdependencies of the emergence and persistence of a circular debt crisis in the electricity sector?

The first sub-question combines an extensive literature study that culminates into an analytical framework and a description of circular debt crises. This sub-question aims to build a knowledge base on the real system's dynamics, distil the relevant concepts for the research, and structure these concepts in an analytical framework.

Sub-question 2: How can the influence of investment decisions on the future electricity system in Pakistan be conceptualised?

The second sub-question aims to translate the key concepts and dynamics found in the literature review and the case study into a conceptual model of the electricity system of Pakistan. The conceptual model is the basis on which the model formalisation in the next sub-question is formulated.

Sub-question 3: What is the effect of different investment and price-setting strategies on the future market price and energy mix of Pakistan?

The third sub-question formalises the conceptual model from the previous sub-question and implements it into the modelling software. By running scenarios with different behavioural settings, the effect on the key performance indicators is explored. Also, the uncertainty of the model is explored by analysing the sensitivity of external variables. The results of the model experiments are analysed for the case of Pakistan.

Sub-question 4: What is the implication of the future electricity system on the development of circular debt in Pakistan?

Finally, the question is answered what the influence is of a change in market price on the circular debt position of Pakistan. This is approached by viewing the model results from a complex adaptive socio-technical system, including the rich set of developments that co-shape the circular debt position.

1.4. Research scope

This research focuses on the effect of the behaviour of investors and market regulators on circular debt in the context of the energy transition. The interventions tested in the agent-based investment mode are based on different behavioural strategies and refrain from testing the effect of policy interventions. However, the interpretation of the behavioural scenarios does provide the opportunity for policy recommendation. Furthermore, the research model focus on the financial implications of investments in generation capacity without quantifying the environmental (dis)advantage. Also, the agent-based model does not numerically model the development of the circular debt burden during the energy transition. The research aims to explain the direction of the causal link between behavioural scenarios and circular debt. Finally, the circular debt crisis is politically sensitive with (geo)-political dynamics shaping actor behaviour. Political factors are used for model conceptualisation and result interpretation, but no political analysis is presented on the circular debt situation in Pakistan.

1.4.1. Societal contribution

If a country finds itself in the downwards spiral of circular debt, the aversive effects can spill over to the whole country, affecting inhabitants and businesses' day-to-day lives. A country experiencing circular debt finds itself in a lose-lose situation. The actors in the power sector value chain are restrained from making more investments, the government can initially compensate with subsidies financed with public debt, but this approach is unsustainable in the long run. What remains is a country suffering, sometimes to the point that other countries or multilateral funds have to rescue a country. However, this comes with political influence, strict financial terms, or reform obligations, which can result in grave consequences for underprivileged inhabitants and businesses. Upward price adjustment is a sensitive policy terrain that influences electoral choice and mobilises public unrest. If such price-changes are substantial, they can topple governments (World Bank 2020, 5). These fierce reactions underline research that indicates that energy accessibility is the main driver of economic growth, poverty reduction and reduction of income inequality (Sarkodie, 2020).

When a country faces a circular debt crisis, it looks at short-term solutions that alleviate the crisis (Jenkins et al., 2015). The actions that follow can very well result in limited climate action. To illustrate the long-term effect of short-term solutions: a decision to build a coal-fired powerplant will emit greenhouse gas until at least 2045.

This research aims to provide insight into the effect of actor behaviour on circular debt in the context of the energy transition. By providing insight into the system dynamic and exploring the effect of different policies, this study contributes to the Sustainable Development Goals (SDG) affordable and clean energy, reduced inequality and climate action, respectively goal numbers 7, 10 and 13. The key performance indicators contracted market price, and energy mix are directly linked to SDG 7 and 13. Policymakers and investors can adopt the research outcome to combine their battle against circular debt with climate change and affordable and reliable energy. Furthermore, circular debt threatens access to electricity predominantly for lower-income people and businesses. Those people are generally unable to afford expensive backup generators to guarantee steady electricity for their business. Those people lose out on basic social needs such as healthcare, education, safe water, and communication when electricity becomes unavailable or too expensive.

1.4.2. Academic contribution

This thesis aims to research the effect of the behaviour of investors and market regulators on circular debt in the context of the energy transition. For this research, a modelling approach is applied to the case study of Pakistan. This study intends to add four insights: (1) an approach to model the potential pathways of the electricity price using an agent-based investment model, (2) integration of decision-making behaviour of a market regulator and investors in an agent-based investment model a single-buyer market structure, (3) linking quantitative model results to qualitative research on circular debt, and (4) include integration cost of variable renewable energy in the agent-based model to expand the perspective on mitigation of circular debt.

1.4.3. Energy investments by FMO, the entrepreneurial development Bank of The Netherlands

This thesis is performed with the support of the Entrepreneurial Development Bank (FMO). FMO focuses on financing private sector investments in selected business sectors, including sustainable energy projects in emerging markets. FMOs portfolio includes Eastern Europe, Africa, Asia, and

Latin America. Providing financial solutions empowers economies, promotes the transition to a low-carbon system, and safeguards energy security (FMO, 2021). The goal of FMO is to stay with their investments within a 1.5-degree pathway, which is the most ambitious target of the Paris Climate Agreement. FMO does this by providing a range of financing solutions such as (syndicated) loans and equity investments for energy generation and distribution projects, off-grid solutions, refurbishments, and efficiency improvements. Being among the first movers, they inspire and encourage other commercial banks and development finance institutions to finance such projects, thereby mobilizing, enhancing, and accelerating positive impacts.

FMO is currently financing ten energy projects in Pakistan, ranging from hydro to solar and wind energy. Together with other development finance institutions and multilateral agencies, FMO engages in efforts to strengthen Pakistan's economy and find (financial) solutions for challenges in the energy sector. For the overarching challenge of circular debt in Pakistan, FMO is in contact with the local public entities and the government to stabilize and improve the sectors' ambitions, policies, and governance for sustainable growth.

Particularly interesting for FMO is the effect of investment behaviour on circular debt and which price setting by the market regulator elicit what kind of investments. Furthermore, viewing Pakistan's energy system through a complex adaptive socio-technical viewpoint provides a novel perspective on the circular debt crisis. FMO's Asian Team supports the research study by sharing its experiences and investment methods. They also provided access to their Pakistan contacts for expert interviews.

1.4.4. Structure of this research

To answer the main research question, this study uses a combination of research methods. In this section, these research methods are discussed and linked to the structure of the sub-questions. Figure 3 presents an aggregated research flow that visually represents the approach of this research. The flow of this research builds on the structure of the research questions. The first research question is answered in chapters 2 and 3, respectively, by constructing an analytical framework and a case study of Pakistan. The following chapter, chapter 4, conceptualises the agent-based model. By doing this, sub-question two is answered. Then chapters 7 and 8 respectively present and analyse the results. This middle section adheres to the third sub-question. Finally, chapters 10 and 11 synthesise the findings and discuss and conclude on the implication of the model results for circular debt. It both answers sub-question four and reflects on the main research question. In doing this, the model results are put in perspective with the analytical framework and the case study of Pakistan.

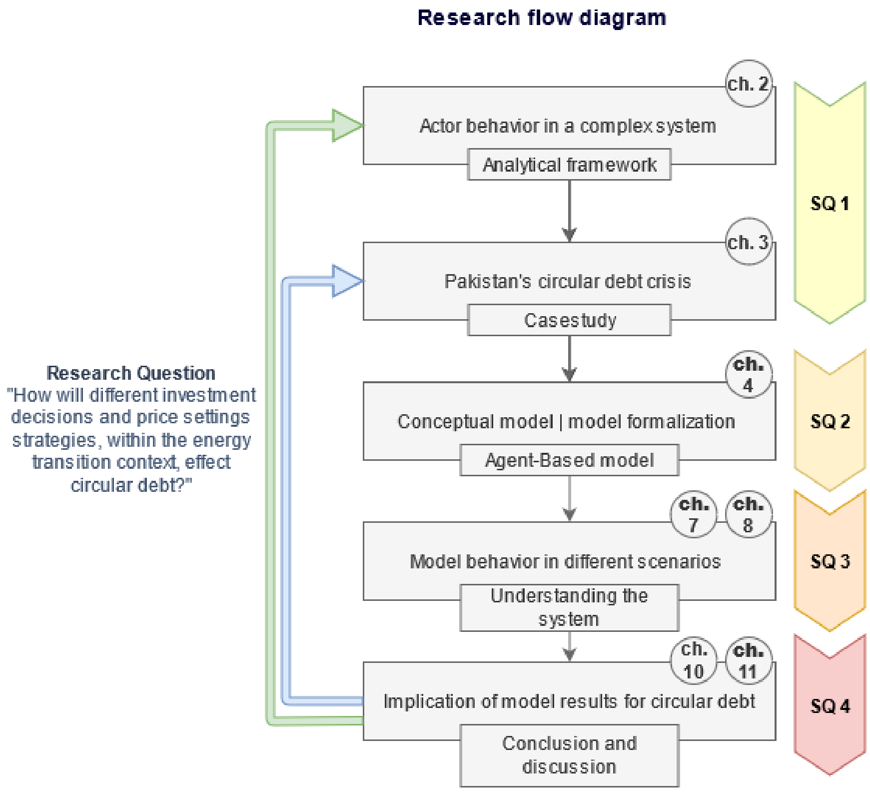

Figure 3: This research flow diagram presents the structure of this research. The grey rectangle boxes show the five research steps. The grey circle refers to the chapter(s) where the research step is discussed. Finally, the coloured chevron arrows show which research step(s) answer the sub-questions.

The chosen research approach aims to describe the effect of the behaviour of investors and market regulators on circular debt in the context of the energy transition. For this research, a modelling approach is applied to the case study of Pakistan. The agent-based investment model is conceptualised based on the analytical framework and the case study. The information for the case study is retrieved via a literature study and interviews with international investment experts. After that, a conceptual model is constructed, which serve as input for the agent-based model. The agent-based investment model is utilized to run behavioural experiments that explore possible future states of the electricity market.

The agent-based modelling approach is chosen over a mathematical optimisation model approach because it is a better tool to deal with the complex adaptive nature of a complex adaptive system where behaviour does not follow the rules of neoclassical thinking (Subramanian et al., 2018). The World Bank (2020a) and National Transmission and Despatch Company [NTDC] (2020) use the optimisation software PLEXOS. Those models have value when it is desired to approach a system with a neoclassical concept of human decision making. This means that the model results are based on actors that have perfect foresight, act rational, and always strive to maximise utility (Kraan et al., 2018). In the politically infused market structure of countries facing circular debt, the assumption of neoclassical thinking does not hold. Therefore, the economic decision-making of institutional economics is adopted for this thesis with a modelling type that is suited for the execution of this decision-making theory. Furthermore, Kraan et al. (2018) suggest that an agent-based modelling approach is a better tool to model the complex adaptive socio-technical nature of the electricity system.

Agent-based models can capture the heterogeneity of actors and behaviours and test multiple possible futures by running the model with various parameter settings (van Dam, 2013; Borshev & Filippov, 2004). A specifically interesting feature of agent-based modelling in the context of this research is the ability to deal with bounded rational actor behaviour, imperfect foresight, and imperfect information (Kraan et al. 2018). The electricity systems under review are not wholesale markets that are built on economic logic. On the contrary, they are systems influenced to a large extent by social and political realities.

A challenge in applying the ABM approach is data availability in the targeted country. An ABM uses many rules and parameters to work properly. Therefore, a rich set of reliable information is essential, which is hard to gather in emerging markets. Secondly, ABM is not suitable to provide a detailed prediction of the future. However, it can explore the effect of different behavioural strategies on debt accumulation and provide insight into actor interaction and its associated influence on the system outcome.

2. LITERATURE REVIEW ON CIRCULAR DEBT IN ELECTRICITY SECTORS OF EMERGING MARKETS

The search for relevant literature for the literature review is executed using a structured an unstructured search process. The literature on the case study is obtained using the structured approach. See appendix A for the full approach.

2.1. The electricity system as a Complex Adaptive Socio-Technical System

Van Dam et al. (2013) describes the electricity infrastructure as a typical socio-technical system characterised by a physical infrastructure containing millions of technological artefacts and a social system involving many actors. The behaviour of those actors is influenced by, among others, market forces, the legislative and regulatory framework, and the broader institutional context (de Bruijn and Herder, 2009). Furthermore, it is an open-ended system that is in connection with other systems such as the petrochemical industry, ICT-sector and the natural environment that absorb waste streams. Finally, it should be recognised that the electricity system is constantly in flux. The system is constantly evolving under the pressure of new legislation and politics (e.g. oil boycotts and Paris Agreement), technological advancement (e.g. cheap renewable energy and battery storage), and adjacent systems (e.g. climate change and economic development).

John H. Holland (Waldrop, 1992) defines a Complex Adaptive System as "*a dynamic network of many agents (which may represent cells, species, individuals, firms, nations) acting in parallel, constantly acting and reacting to what the other agents are doing. The control of a CAS tends to be highly dispersed and decentralized. If there is to be any coherent behavior in the system, it has to arise from competition and cooperation among the agents themselves. The overall behavior of the system is the result of a huge number of decisions made every moment by many individual agents"*.

This definition by Holland does justice to the high amount of agents in the electricity market (e.g. investment firms, national governments, regulators, consumers) who constantly interact and make numerous decisions that lead to nonlinearity, emergence, and dynamic behaviour (Nikolic, 2009). According to Nikolic (2009, 32), adopting the Complex Adaptive System view makes it possible to view and model the dynamic patterns of system behaviour emerging from local level interaction. When viewing the research question through the complex adaptive system theory lens, the circular debt problem evolves in a country through the interaction of actors with other actors and their (technical) environment.

Researchers have recognised the complex adaptive nature of electricity systems for quite a while. To make the complex adaptive nature more concrete for a single buyer electricity market a conceptual approach is presented in Figure 4. The figure shows the interconnectedness between the physical and institutional layer operating of the electricity system. The physical layer concerns the actual electricity flow from the point of generation via the transmission and distribution network to the place where the electricity is consumed (Course reader, SEN1522 Electricity and Gas, CoSEM master, TU Delft, 2019). The institutional layer consists of actors in dark blue controlling the physical and regulatory part of the system and actors in light green that operates within the institutional boundaries of the system.

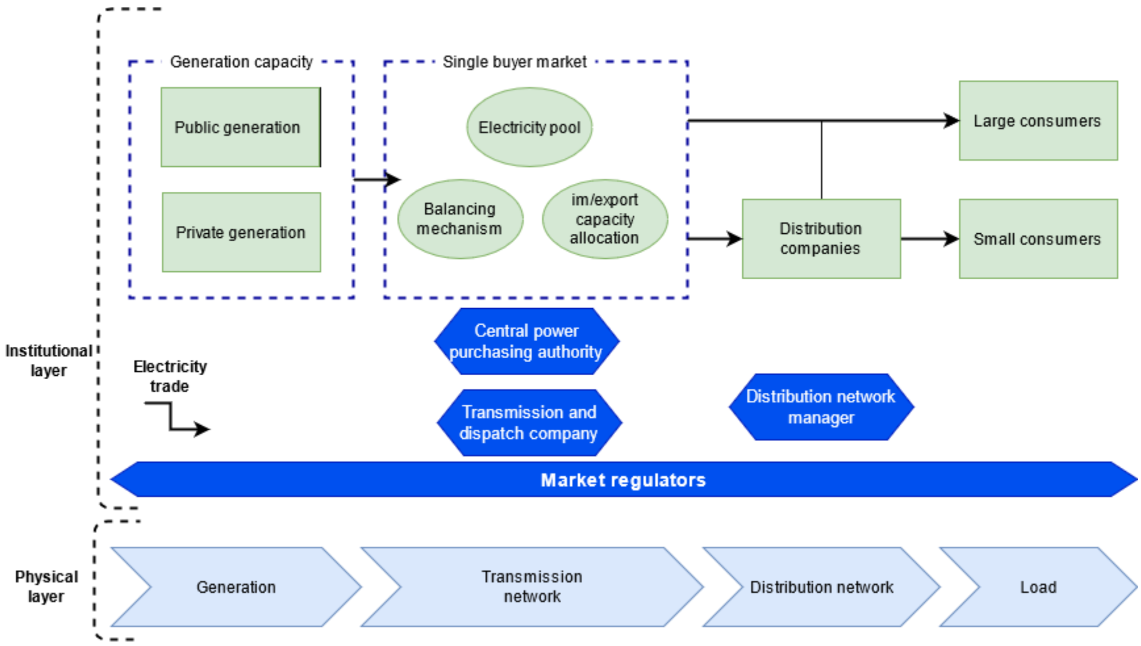

Figure 4: A conceptual approach of a single buyer electricity system. The diagram shows distinguish between the physical layer (light blue) and the institutional layer (dark blue and green). The dark blue octagons are supervisory entities. The green rectangle boxes represent actors active in the electricity value chain. Adapted from Course reader, SEN1522 Electricity and Gas, CoSEM master, TU Delft, 2019.

The institutional layer's goal is to ensure that the system functions according to the goals of reliable, affordable, and accessible electricity provision. For this, the actors in dark blue constantly enforce and redefine a framework of institutions within their mandate. This process is in constant flux as the physical layer and actors in the institutional layer bring forward behaviour that triggers a reaction. The physical layer has been built over decades, asks for huge investments with long lead times over long pay-back periods and which a myriad of various construction, financing and tariff-setting contracts.

Concept: electricity system as a complex adaptive socio-technical system

This study views the electricity system as a complex adaptive socio-technical system. By recognizing this view, the perspective on circular debt is based on the idea that individual behaviour and interaction lead to nonlinear, emergent, and dynamic behaviour.

2.2. Circular debt as expressed as a complex socio-technical problem

In the past decades, some emerging countries saw their power sector slid into a financial crisis. For example, the Philippines power sector was in a crisis after a chain of events laid a debt claim on the government, equalling 25% of the national debt. It started in 1993 with the decision to give out generation contracts to private companies with generous protection. Then the East Asian financial crisis hit the Philippines hard, which made the demand for electricity drop and devaluated the currency. The generous contracts which laid the currency and demand risk at the government became an unbearable burden that crumbled the government's financial position in 2001 (World Bank 2020a, 155). This example illustrates that a chain of events can trigger a power sector crisis, which can easily translate into a macro-fiscal crisis due to the weight of the electricity sector (World Bank 2020a, 154).

The power sector crisis of Pakistan during the 2000s took such a specific form that the phenomenon received its own name: circular debt (Kessides, 2013). After the definition was coined, its use was adopted to name similar situations in other countries[5]. Box 1 defines circular debt by Pakistan's Economic Coordination Committee (National Power Tariff and Subsidy Policy Guidelines, 2014) that include multiple components related to circular debt.

Box 1: Definition of circular debt (National Power Tariff and Subsidy Policy Guidelines 2014)

Circular debt was officially defined by the Economic Coordination Committee of the Pakistan Cabinet in 2014 as follows: "Circular debt is the amount of cash shortfall within the Central Power Purchasing Agency (CPPA) which it cannot pay to power supply companies. The overdue amount is the result of: (a) the difference between the actual cost and the tariff determined by the National Electric Power Regulatory Authority (NEPRA) which is the distribution company's loss over and collection under that allowed by NEPRA; (b) the delayed or non-payment of subsidies by government; and (c) delayed determination and notification of tariffs." (National Power Tariff and Subsidy Policy Guidelines, 2014)

For the scope of this research, the definition of circular debt is generalised in the fashion that covers the essence of circular debt without the country-specific situation. A broader definition is as follows:

"*Circular debt surfaces when distribution companies lack the revenue to cover all their costs, and the government fall behind on its subsidy payments, so distribution companies cannot honour their power purchase bills with the single buyer, who cannot keep up with payments to generators, which in turn do not pay their fuel suppliers".*

Both definitions bring forth essential concepts that distinguish circular debt from other power sector crises: (1) it is a self-reinforcing "vicious circle" without proper solution, (2) all actors in the value chain are confronted and at least all public entities accumulate debt including the central government, (3) it does not occur in a wholesale market (4) the inception point is the mismatch between the sectors full-cost recovery tariff and revenue from electricity sales to consumers due to a restricted electricity tariff by the government (5) the government fall behind on subsidy payments.

During the 1990s, a new paradigm for power sector design was put forward that promoted unbundling, privatization, maximum competition, and the introduction of an independent regulator to oversee the monopoly-prone parts of the system (Heller and Victor, 2004; The World Bank 2020a, xxix). In the wake of this so-called 'Washington Consensus' researchers have debated extensively about the effects of this view on market reforms.

The papers by Bacon and Besant (2001), Zhang et al. (2008), and the report by the World Bank (2020a) show the progression in thinking on this matter. Bacon and Besant-Jones (2001)

[5] Other countries facing/faced circular debt: Ghana, Zambia, Honduras and Haiti

conclusions are in line with the Washington Consensus. They argue that the development of the power sector is aided by introducing policies to attract more private investment. This includes a more robust legal and regulatory framework, privatization of the distribution companies and plans for a wholesale market. Seven years later, Zhang et al. (2008) concluded that the effects of reforms are well documented. They argued that most emerging markets' reforms did not produce the intended benefits due to serious institutional weakness.

Nevertheless, based on a 35-country survey, they also concluded that emerging markets are still willing to engage in reforms despite the drawbacks. However, the reforms are more cherrypicked, with competition among electricity generators consistently valued over privatization and the introduction of an independent regulator. The World Bank (2020a) recently reflected on the endeavour of 25-year Washington Consensus inspired policy and concluded that the one-size-fits-all approach was unsuccessful in many cases. They call for future policy that is context-dependent, outcome-oriented instead of driven by predetermined processes, and they recognise that alternative institutional pathways can also lead to desirable outcomes.

This view resonates with case specific research on Argentina and Nigeria respectively by Haselip et al. (2005) and Arowolo and Perez (2020). Haselip et al. (2005) write that initially successful large-scale privatization of distribution and generation companies turned sour after the 2002 financial crisis, leading to strong currency devaluation in Argentina. This resulted in a lose-lose situation for inhabitants who felt agitated by looming tariff hikes whilst the business community felt trapped because of melting profits. The agitation by inhabitants was fuelled by the fact that before the crisis, private operators expatriated large profits pre-crisis to the USA or Europe. In the case of Nigeria, Arowolo and Perez (2020) argue that the 2010-2013 power sector reforms are undoubtedly adjudged unsuccessful by most stakeholders. Politt (2008) argues that the privatized power sector coped with the economic shock much better than the previous system would have. According to Arowolo and Perez (2020), failure lay in economic, institutional, technical, financial, and socio-political challenges that were exacerbated by a financial crisis.

Extensive knowledge on cases explicitly related to circular debt is not present. Literature on Pakistan's circular debt crisis dominates the scientific library. Das Valasai et al. (2017) specify a whole range of reasons why the circular debt crisis is still ongoing. The paper points towards insufficient generation capacity because of an unfavourable investment climate maintained by political instability, institutional shortcomings, and bureaucratic procedures. They also discuss the interest groups benefiting from market disorder, mismanagement, and corruption that results in a poor rate of electricity bill recovery. Rauf (2015) adds that the historical decisions put Pakistan on a certain path plagued with load shedding, debt and deteriorated quality of transmission net, which is hard to leave.

In sum, power sector reforms in emerging countries have failed under the standard policy model and reform process (Williams and Ghanadan, 2006). Therefore, power sector crises such as circular debt crises should be approached with an acknowledgement of the complex adaptive nature of the electricity sector. The embrace of the complex nature goes hand-in-hand with a broader conceptual view on the power sector reforms. The theories of Williamson (1998) and Glachant and Finon (2000) about the effect of informal institutions on the development of formal institutions feed this broader conceptual view. Also, de Vries and Correljé (2008) work on formal institutional factors help to structure the complexity of power market reforms. From the just mentioned researchers, the most important factors relevant to this research are summed in Table 3.

Table 3: Factors that determine the context of the restructuring process (adapted from; Vries and Correljé, 2008)

	Factor	Impact
Physical factors	Natural endowment with energy sources	The presence or absence of primary energy sources drives the choice of primary fuels, the technical and

		economic characteristics of the sector and drives interests and policies
Economic factors	Level of economic development and growth	Influences demand growth, the potential for investments and institutional stability
	Financing options	Especially in developing or transition countries with a weaker economy financing options may be limited
Institutional factors	Institutional stability and rule of law	Facilitates investments and external funding; stabilizes and provides coherence in policies; helps align policies, regulations, and the legal framework
	Degree of institutional centralization and homogeneity	The power of the central government influences the coherence of policies and their support in terms of regional, sectoral, and social dispersion
	Influence of stakeholders	Strong stakeholders may be able to influence reforms in their own interest

In section 2.1. the conclusion is drawn that the electricity sector is a complex adaptive system. If then the circular debt crisis is viewed through the lens of the definition of a complex adaptive system by John H. Holland, the perspective should change from the system level, top-down, orientation as the strategy was under the Washington Consensus to an agent level, bottom-up approach.

Concept: circular debt as an expression of a socio-technical system

1. This study views circular debt as a shortfall of cash throughout the value chain due to (i) a lack of revenue by the distribution companies to cover all their costs and (ii) the government falling behind on their subsidy payments.
2. Circular debt is viewed as a challenge to be solved within a complex adaptive system.

2.3. The worldwide energy transition is a game-changer in the approach of circular debt

Renewable energy is a game-changer that influence all aspects of a country's energy supply, ranging from high-level geopolitics and climate change to national infrastructure topology and market operations to local level decentral generation and business case opportunities (Scholten et al. 2018, 5). researchers from all kinds of disciplines tumble over each other to explain the implications of renewable energy for their field of research. For example, Scholten et al. (2018, 17) present an analytical framework that focuses on the change in interstate energy relations based on renewable energy systems' geographical and technical characteristics. Secondly, Jenkins et al. (2015) bring forward a conceptual review of the recently emerged research field of energy justice. In this field, justice principles are applied to, among others, energy policy, energy production, energy security and climate change. It explores the social implications of the renewable energy transition. Thirdly, Hepstonstall and Gross (2021) review the integration costs of variable renewable energy. Finally, Qazi and Jahanzaib (2018), Zameer and Wang (2018), Shaikh et al. (2015) and Sadiqa et al. (2018) discuss the relationship between electricity prices, renewable energy, and circular debt. In this context, they present policy recommendations or frameworks aiming to mitigate the circular debt crisis. This small selection of research fields affiliated with this research already shows the massive complexity VRE integration brings to a country.

All the studies mentioned above bring forward considerations that are taken into account by investors and market regulators. For this study, the energy transition research fields are demarcated to the essential dynamics concerning the research question: generation cost, renewable energy integration and dependence on fossil fuel (Ueckerdt et al. 2015; Zameer and Wang, 2018; Hepstonstall and Gross, 2021).

According to Mahmood et al. (2014), there is a direct link between the cost of energy production and circular debt. Mahood et al. (2014) draw this conclusion based on the case of Pakistan, where the government is legally bound through PPAs to compensate private power producers for higher fuel prices. In Pakistan, the last decades show that compensation for higher fuel prices is a burden too much for the government, which reacts with a delay of subsidy payment, resulting in higher circular debt (Bacon, 2019). Qazi and Jahanzaib (2018) also point out that the increased cost of generation aggravates circular debt because the single buyer and transmission grid operator cannot recover the higher cost due to inappropriate administrative control and financial constraints. If higher generation costs increase the circular debt burden, lower generation cost will probably also reduce the debt burden (The World Bank, 2020a; Sadiqa et al., 2018). With the drastic decline in generation cost for renewable sources and the price risk related to fossil fuel, it is not surprising that researchers point towards renewables as a solution for circular debt (Heptonstall et al., 2020; Sadiqa et al., 2018).

It would, however, be too narrow to conclude that more renewable energy will, per definition, bring the cost of generation down. There are also downsides to VRE, which are tied to the intermittent nature of VRE. The ‘drastic decline’ mentioned in the previous paragraph is based on the financial measure called *Levelized Cost of Electricity* (LCOE). This measure is the preferred choice of researchers, governments, and NGO’s to report and compare electricity prices per generation type (Aldersey-Williams & Rubert, 2019). LCOE is based upon a [discounted or undiscounted] -cash flow during the whole life cycle of the project with costs and revenues of generators/generation and divided by the aggregate amount of electricity generated: this provides the comparable cost in the unit format € per MWh (Heptonstall et al. 2021). However, this method is limited because it does not consider the additional measured necessary to compensate for the variability of VRE systems (Joskow., 2011; Ueckerdt et al., 2013; IEA, 2020). The IEA developed their own measure called ‘the value adjusted LCOE’ (IEA, 2020).

The value adjusted LCOE tries to include the broader system cost by including the value of three systems services: energy value, flexibility value and capacity value per technology (IEA 2020, 76). The energy value is calculated as the average price received per unit of generation for a year based on least-cost merit order dispatch and simulated wholesale electricity prices (IEA 2020, 76). It is the value with the largest weight in the calculation of the value adjusted LCOE and varies considerable per technology, region and penetration of variable renewable energy. The capacity value indicates the portion of the installed capacity that can reliably be available during times of peak demand. For dispatchable powerplants, the capacity value is ~95%, but for intermittent sources such as solar and wind, this is more in the range of 0 – 60%, with solar at around 20% and wind at the higher end of the range depending on the construction site (IEA 2020, 78). The last component is the technology flexibility value. This value encompasses non-energy ancillary services required in the electricity market, such as primary and secondary reserves, frequency regulation, and synchronous inertia (IEA 2020, 78). Value adjusted LCOE still relies on rough estimates, resulting in high uncertainty margins (IEA, 2020). Furthermore, the value has significant regional differences, which make generalisation among countries and regions unreliable. The IEA has not published value adjusted LCOE data for countries or regions.

A recent review paper by Heptonstall and Gross (2021) combined 600+ data points to form a rough estimation of the profile costs, like the earlier mentioned definition of capacity value. The result of the study provided a range of cost estimates (unit: €/MWh) for VRE integration at different VRE penetration levels. It showed that VRE integration costs could be below €20 per MWh for countries with a renewable penetration of <35% and even lower or negative for VRE penetration closer to zero (Heptonstall and Gross, 2021). Crucial for interpretation of the cost values is that the largest VRE profile cost drivers are specific geographical/regional/local factors that affect the supply/demand correlation and power system characteristics that determine the flexibility of operation. One geographical difference is that countries with warmer climates use air conditioning with a demand peak at noon that coincides with solar PV production peak (Heptonstall and Gross, 2021). In such a case, intermittency is less of a problem compared to European countries with evening peaks of electricity demand. With 90% of all data coming from Europe, a generalization to emerging markets comes with significant uncertainties.

To finalize this section, a reflection on the most important barriers for price-setting and investment decisions for new renewable energy projects. Barriers regarding the behaviour of investors or market regulators are context-dependent. See, for example, the three institutional barriers, in the context of Pakistan, mentioned in Table 3 (a) institutional stability and the rule of law, (b) degree of institutional centralization and homogeneity, (c) influence of stakeholders. In Pakistan, the public entities required to provide approvals for the construction of a new RE project are considered by some experts as fragmented and with bureaucratic processes (personal interview, 17-06-2021, see appendix C.5). This resulted in the Pakistan case that it took almost ten years before the first RE project was realised after the government introduced a regulatory framework.

Furthermore, in Pakistan, the investment opportunities are made available by the government. This means that when the government does not make projects available, no investment will be made. This contradicts with wholesale markets, where the investors can lead the process for new RE investments. Also, investors in Pakistan receive a price offer from the market regulator for new investments with very limited space for negotiation (personal interview, 17-06-2021, see appendix C.5). This offer is regardless of the current price paid for electricity. In Pakistan, the prices for RE projects are, according to an international investor, 'rock bottom' which only attract the most progressive investors (personal interview, 17-06-2021, see appendix C.5). Lastly, the influence of the incumbent players in the coal business is very effective in frustrating the political decision-making regarding renewable energy. Because the market is politicized, the influence of these incumbent players is significant. Even though there are many more barriers than the three mentioned before, these are the most important ones for investments decision-making in the context of the energy transition.

Concept: the worldwide energy transition is a gamechanger in the approach of circular debt

1. This study acknowledges the vast implications that the energy transition has on society.
2. Due to the complexity and breadth of the implications, the study is demarcated to the following research field related to circular debt: (1) generation cost, (2) renewable energy integration, and (3) dependence on fossil fuel.
3. The study internalizes the costs of capacity value associated with the variability of renewable energy. It is recognized that the available data still bears significant uncertainties.

2.4. Behaviour under circular debt

This research looks at the investment behaviour of investors and the price-setting by market regulators. The goal for regulators is to ensure reliable, accessible, and affordable electricity (Course reader, SEN1522 Electricity and Gas, CoSEM master, TU Delft, 2019, p7; Sarkodie and Adams, 2020). The goal for investors depends on the nature of the investors. In general, this can be split into two large groups: (i) development finance institutions (DFI's) and (ii) commercial (foreign) investors.

The goal of DFI's is to finance projects for sustainable economic growth, battling climate change and reducing inequality (EDFI, 2019). DFI's finance projects with high risks that otherwise would not acquire adequate funding (FMO, 2021). They operate only in emerging countries and hardly invest in fossil generation capacity (Bruck, 1998). On the other hand, commercial investors are maximum profit-seeking entities that engage in lower-risk investments (WRI India 2021, 16). Typically, DFI's provide loans to project developers or countries to boost renewable energy when commercial banks mark an investment too risky (WRI India 2021, 16). When the share of renewables grows, and investment risks have been reduced, a more considerable inflow of private investments and debt pours in, dwarfing DFI's market share (WRI India 2021, 16). Developing and emerging markets tend to rely on foreign sources for investments (Sarkodie, 2019). This brings two downsides: loans are often in foreign currencies bringing exchange rate risks, and profits are extracted from the economy (Bacon, 2019). This typical sequence happened to India when renewable energy grew from almost zero to 24% of total installed capacity in two decades. India's finance is, however, atypical in the strong growth of domestic sources for finance (WRI India 2021, 10).

To attract investment from DFI's and commercial investors in the energy sector, emerging markets heavily rely on feed-in tariffs policies (FIT) or cost-plus tariffs that combine long term, fixed-price electricity purchase agreements and guaranteed grid access (Huenteler, 2014). When a market regulator grand a FIT or cost-plus tariff, the risks on the investor's side is largely covered. This makes FITs popular to attract foreign investment (Huenteler, 2014). Setting the price of a FIT is a trade-off between affordability and security of supply. For affordability, the FIT tariff is pushed as low as possible, but the security of supply pushes the price up again to ensure enough investments such that production keeps pace with demand (Pueyo, 2018).

All the information above is about what kind of trade-offs and goals do market regulators and investors pursue. The question of how those actors make economic decisions given is in the domain of economic science. This research needs to have a conceptual framework of how the market regulator and investors behave and allocate their scarce financial capacity. In economics, there are different theories to view decision-making by human beings. Two popular theories are neo-classical economics and institutional economics. Neoclassical economics look at humans as rational actors with perfect information and foresight (Groenewegen, 2004). Institutional economics question this perspective and cultivate the idea that there are actors with a heterogenic set of goals (i.e. not only profit maximisation) are bounded rational and that decisions are shaped by a body of institutions that is an endogenous part of the market (Groenewegen, 2004; Course reader, SEN1522 Electricity and Gas, CoSEM master, TU Delft, 2019). These institutions are rules (i.e. formal and informal) that structure economic, social and political behaviour (Hazeu 2007, 139). According to Willemson (1998), institutions are shaped over time by the interaction between political, economic, and physical factors.

Both economic theories are used as the basis for financial models that include human decision-making. For example, the recent model by The World Bank (2020) on renewable energy development in Pakistan use the neoclassical concept of human decision-making as it models the optimal investment trajectory under different scenarios. For an optimal investment strategy, the model relies on perfect foresight and rational actor behaviour.

Kraan et al. (2018) acknowledge that these models have provided key insights for business developers and policymakers in centrally planned systems but state that those models are not working for complex adaptive systems. The paper concludes that models based on neoclassical decision-making provide outcomes, not in line with the literature and real-world observations. Kraan et al. (2018) state that decision-making is heterogeneous, bounded rational, and includes imperfect foresight. Therefore, Kraan et al. (2018) suggest that the agent-based modelling approach is a better tool for modelling the before-mentioned aspects in a complex adaptive system.

Concept: behaviour under circular debt
In this research, decision-making by actors is viewed through the lens of new institutional economics.

2.5. Analytical framework

Combining the insights from the previous four sections, the following framework with three steps (see Figure 5) emerged.

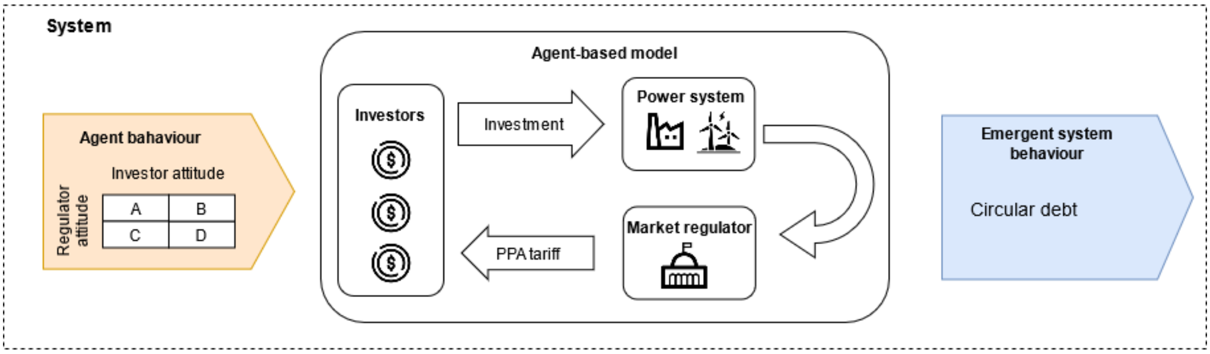

Figure 5: Analytical framework of the circular debt system (design adapted from Scholten et al., 2018)

The three steps of the model represent an input-output model that presents the independent and dependent variables. On the left are the independent variables that consist of different behavioural strategies from the market regulator and investors. This influences the dependent variable circular debt on the right side. As mentioned above, more renewable energy can reduce circular debt, but whether this happens, and to which extent, depends on the behaviour of investors and market regulators.

3. CONTEXT OF THE ELECTRICITY SECTOR AND CIRCULAR DEBT IN PAKISTAN

Exploring the potential of variable renewable energy to solve the circular debt crisis requires taking a step back. Pakistan's current challenges are embedded in a complex social and technical system formed over many years. In those years, the Government of Pakistan (GoP) created institutions and policies to solve imminent problems, react to political issues or adhere to the “Washington Consensus” aim for privatisation and unbundling. The contemporary challenges are the consequence of the decisions made as early as 1994.

This chapter provides insight into the Pakistan case study by explaining (I) the general profile of the country, the domestic tensions, and their geopolitical position, (II) current generation mix and VRE potential, (III) electricity market structure and the actors' formal mandate, (IV) the current and projected circular debt burden and the root causes of circular debt. The insights from these sections are essential for understanding the socio-technical context of Pakistan’s electricity sector and is used in the conceptualisation of the model, design of behavioural strategies and interpretation of model results.

3.1. Country profile

Pakistan is an emerging country with 207 million people (2017 census) divided into 32.2 million households (Bacon 2019, 33). People live in four provinces (Khyber Pakhtunkhwa, Balochistan, Punjab, and Sindh), one capital territory (Islamabad Capital Territory), two autonomous and disputed territories and the Federal Administered Tribal Areas (International Finance Corporation [IFC] 2016, 10). Currently, Pakistan is a federal parliamentary republic with the Pakistan Tehreek-e-Insaf (PTI) as the current ruling party. In 2013-2014, 53 to 59 million people lived in poverty with an income lower than PKR 3,030 Rupees (19.47 US dollars[6]) per month (Redaelli 2019, 8). Pakistan's GDP is 276 billion US dollars (PKR 42,744 billion rupees), with real GDP growth between 1.9 – 5.5 percent between 2010 and 2019 (International Monetary Fund [IMF] 2020, 146). The Covid-19 crisis hit the Pakistan economy, resulting in the first contraction in decades.

Figure 6: map of Pakistan © www.mapsofworld.com

[6] Throughout this thesis the same exchange rate is applied. Exchange rate of 14 November 2019 PKR $ 1.00 = US$ 155.45. See appendix K for a 10-year exchange rate graph.

The roots of Pakistan lay in the separation of British colonial India into two, and later three major pieces: India, Pakistan, and Bangladesh (Marshall 2015, 195). After the announcement of the British House of Commons, an extraordinary movement of people followed. The separation was based on religious groups. Millions of Muslims fled from the just established India to the newly founded Pakistan. Hindus and Sikhs moved in the opposite direction. It was carnage. People from different religious groups turned on each other in panic and fear, resulting in at least one million deaths and 15 million displaced (Marshall 2015, 195).

The separation did not favour Pakistan. It received only 17 percent of the financial reserves which the pre-partition government controlled. Furthermore, it got a small proportion of the taxable income base, industry, and major cities. Also, Pakistan inherited the pre-separation troublesome border, the Northwest Frontier (Marshall 2015, 196-197).

The different regions in Pakistan all have their language and culture. Pakistan tries hard to cast a nation with a unified national identity, but it remains rare for a Punjabi to marry a Baluchi or a Sindh to marry a Pashtun (Marshall 2015, 197-198). There is a deep divide between regions that cause tension and opposition. People in Sindh feel as if they are treated as second class citizens by Punjabi (Marshall 2015, 198). The Pashtuns of the North-West Frontier have never accepted the rule of outsiders at all (Marshall 2015, 198). Baluchistan has an occasional uprise demanding independence. Finally, there are religious tensions. With antagonism shown to the Christian and Hindu religious minorities. Moreover, there is tension between Sunni Muslims and the minority Shia Muslims (Marshall 2015, 198).

The interstate relationship with China and the USA is a geopolitical affair that determines Pakistan's bargaining power on the global stage. The relationship with China is strong despite the modest physical connection. The relation is built on the strategic positing of Pakistan. China's need for energy imports can be diversified with an overland imports route through Pakistan starting at the port of Gwadar in Balochistan. This route bypass the Strait of Malacca, a choke point for Chinese economic growth (Marshall 2015, 199). The cooperation between both countries is formalised in the China-Pakistan Economic Corridor. Part of this corridor is Chinese investments in a deep-water port in Gwadar, a 40-year lease on 2,300 acres of land in the port area and an international airport. Furthermore, China and Pakistan agreed on a $46 billion deal to build a superhighway of road, pipelines and railways running 2900 km from Gwadar to China (Marshall 2015, 199). The Pakistan government trumpet their relationship with China as ‘taller than the mountains and deeper than the oceans’ (Marshall 2015, 201). Even though this is not true it is sometimes useful to make the Americans nervous about cutting Pakistan off from the massive financial aid it receives from the USA.

3.2. State of the industry

In section 3.1. a brief overview of Pakistan was given. In this section, we take a closer look at the electricity sector of Pakistan. First, it is discussed where the electricity is consumed using a population density map of Pakistan (Figure 7). Many people live in the big cities in the north (e.g. Islamabad, Lahore and Peshawar), but the area near the Indus and its tributaries are also densely populated. Pakistan possess considerable coal reserves but have no oil & gas reserves.

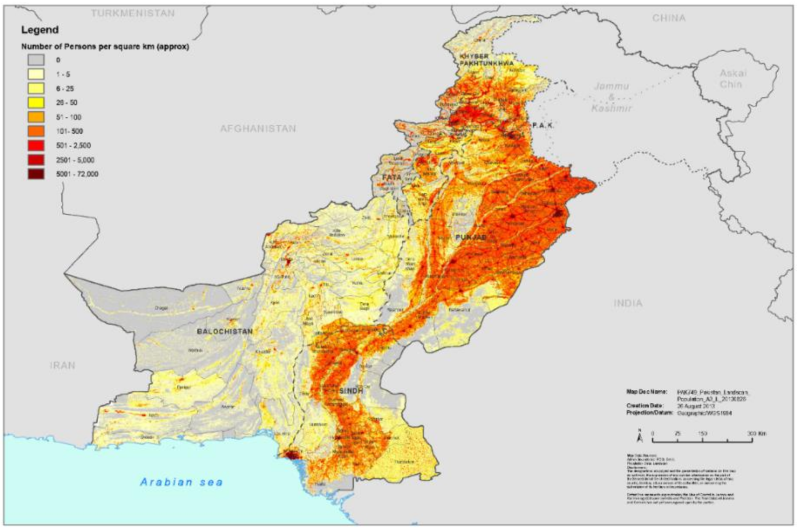

Figure 7: A population density map of Pakistan. The majority of the population lives in the north-east and on the banks of the large Indus River. (United Nations Office for Coordination of Humanitarian Affairs [OCHA], 2013)

Electricity mix

The total installed capacity of Pakistan on the 30th of June, 2020 was 38,719 MW (NEPRA 2020, 33). In contrast, the installed capacity for the Netherlands in 2018 was 25,600 MW. This is, however, with a population more than ten times as small (Sonnichsen, 2020). The breakdown of the installed capacity to generation type is provided in table 1.

Table 4: Pakistan's generation mix in 2004 and 2020. The table shows a strong dependence on fossil fuel and hydro power. WAPDA is the deparment of waters and exploite public dams. K-electric is the privately owned distribution company. For simplicitly, only the total generation capacity is presented for the K-electric system. (National Electric Power Regulatory Autority [NEPRA], 2020; NEPRA, 2006).

Generation type	2004 (MW)	2020 (MW)	2004 share in total (%)	2020 share in total (%)
WAPDA Hydro (public)	6,463	9,389	33	24
IPPs hydro (private)	30	472	0	1
Total Hydro	**6,493**	**9,861**	**33**	**25**
Thermal GENCOs (Public)	5,159	4,881	26	13
Private Thermal	5,715	17,276	29	45
SPPs/CPPs	-	340	0	1
Nuclear	-	1,330	0	3
Total: Thermal including Nuclear	**10,874**	**23,827**	**55**	**62**
Wind	-	1,248	0	3
Solar	-	430	0	1
Bagasse/Biomass	-	369	0	1
Total renewable energy	**0**	**2047**	**0**	**5**
K-electric system (private)[7]	2310	2,948	12	8
Total Generation	**19,677**	**38,719**	**100**	**100**

The generation mix shows a strong dependence on thermal energy and hydro energy. Over time the share of thermal (including nuclear) increased compared to hydro. Renewable energy is a new phenomenon that started only last decade and has a marginal share in the electricity mix.

[7] K-electric is a private vertical integrated utility in the Karachi area

Current and past electricity supply & demand

A persisting challenge for Pakistan is to produce enough electricity to meet the consumer's demand. From 2005 onwards, consumers faced up to eighteen hours per day of load shedding (i.e., no electricity at all) (Qudrat-Ullah, 2015). The supply-demand gap peaked in 2016-2017 at 6000 MW. Table 5 provides an overview of the generation capability and the peak hour demand over the last six fiscal years.

Table 5: Electricity demand and supply. The generation deficit changed to a surplus between 2015-16 and 2019-20 (NEPRA 2020, 156)

Year (FY ends 30th June)	Generation Capability (MW)	Peak Hour Demand (MW)	Surplus/deficit
2015-16	17,261	22,559	-5298
2016-17	19,020	25,117	-6097
2017-18	23,766	26,741	-2975
2018-19	24,565	25,627	-1062
2019-20	27,780	26,252	1528

The demand and supply trend shows a positive trend towards a generation surplus. Despite this achievement, some districts still experience periods of load shedding (NEPRA 2020, 27). To keep a generation surplus will be challenging because the expectation is that demand doubles in the upcoming decennium to 44,308 – 48,074 MW[8] in FY 2029-30 (The World Bank 2020b, 80).

VRE potential

The high solar irradiance throughout the whole country stands out. Figure 8 shows the solar irradiance of Pakistan. Around the densely populated Islamabad, the daily irradiance is around 4.0 KWh/kWp, which is high compared to the Dutch maximum of 3.1 kWh/kWp (Solargis, 2021). The irradiance in the southwest Balochistan province is very high, but the land is sparsely populated. For electricity production, this is a disadvantage because extensive transmission capacity is needed to transport the electricity to the consumer.

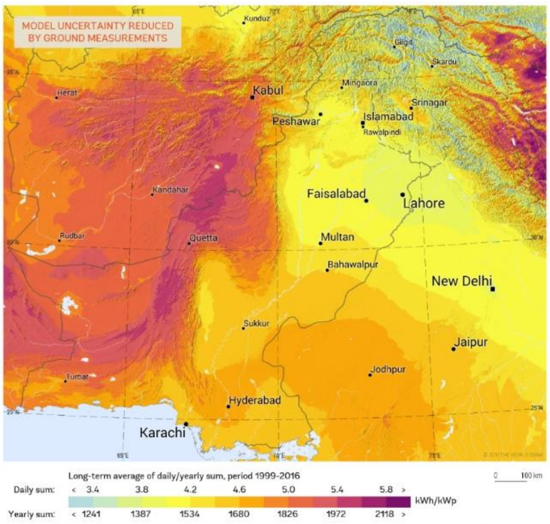

Figure 8: Photovoltaic Power Potential Pakistan. There is a high solar irradiance throughout the whole country © 2020 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis.

[8] The lower range of the interval are forecasts of the National Transmission and Distribution Company (NTDC) and the lower end of the interval is a adapted forecast by The World Bank. The range is based on the 'normal' scenario provided by The World Bank.

The next variable renewable energy alternative is wind energy. Figure 9 shows the mean windspeeds in Pakistan. On average, the wind speed is relatively low compared to windy countries. For example, the Netherlands have an average windspeed of around 7 m/s (Global Wind Atlas, n.d.). The windspeed in the western region of Balochistan is the highest of the country, but this region is prone to civil unrest and sparsely populated.

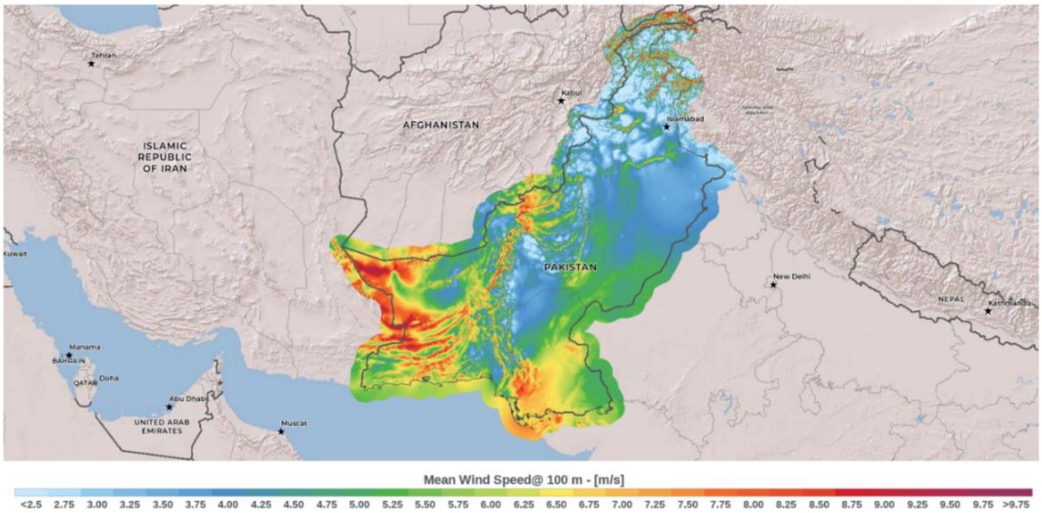

Figure 9: Mean Windspeed Map of Pakistan on 100m. Average wind speeds in the densely populated northeast are 3 – 5 m/s which is relatively low. In the southeast windspeeds are average with 5 – 8 m/s. In the Netherland windspeeds average 7 m/s © The World Bank, Source: Global wind Atlas.

3.3. Contemporary electricity market structure

The electricity sector of Pakistan underwent significant reforms in the wake of the '90 Washington consensus by the IMF and World Bank. These reforms aimed to keep pace with the growing electricity demand while conserving reliable, safe, and affordable electricity. Due to a mix of political and economic reasons, dating back to 1994, the electricity market did not develop with the envisioned result. On the contrary, Pakistan is facing a severe energy crisis that threatens vital parts of the economy and damages the country's long-term development (Sahir & Qureshi, 2007).

The organisational structure of the electricity sector of Pakistan emerged over decades of political decision-making. The current structure is depicted in Figure 10. The Ministry of Energy is responsible for the smooth operation of the electricity sector. Therefore, it is involved in the decision-making of the public institution in the white rectangle boxes. Below the Ministry of Energy is NEPRA. The market regulator is responsible for a regulatory framework that ensures safe, reliable, efficient, and affordable electricity. The Central Power Purchasing Authority is the single buyer that buys electricity from the generators and sells it to the distribution companies (see Figure 1 for a typical single buyer market structure). The National Transmission and Dispatch is the high voltage, grid operator. The Alternative Energy Development Board is established in 2003 as an autonomous body to promote and facilitate renewable energy projects in Pakistan (IFC 2016, 16). The Pakistan Electric Power Company (PEPCO) is established to guide the unbundling process. Currently, unbundling has low priority and shifted the focus to overseeing the administrative matters of public generation, distribution, and transmission companies (grey rectangles). The Private Power and Infrastructure Board provide advice to the GoP on matters concerning private generation investments. Finally, the Ministry of Water develops and operates hydro generation capacity.

NEPRA, the Independent Power Producers, the CPPA, and the distribution companies are pivotal actors in the value chain that affect and influence circular debt. Therefore, these actors are discussed in greater detail below. The other actors are discussed in Appendix M.

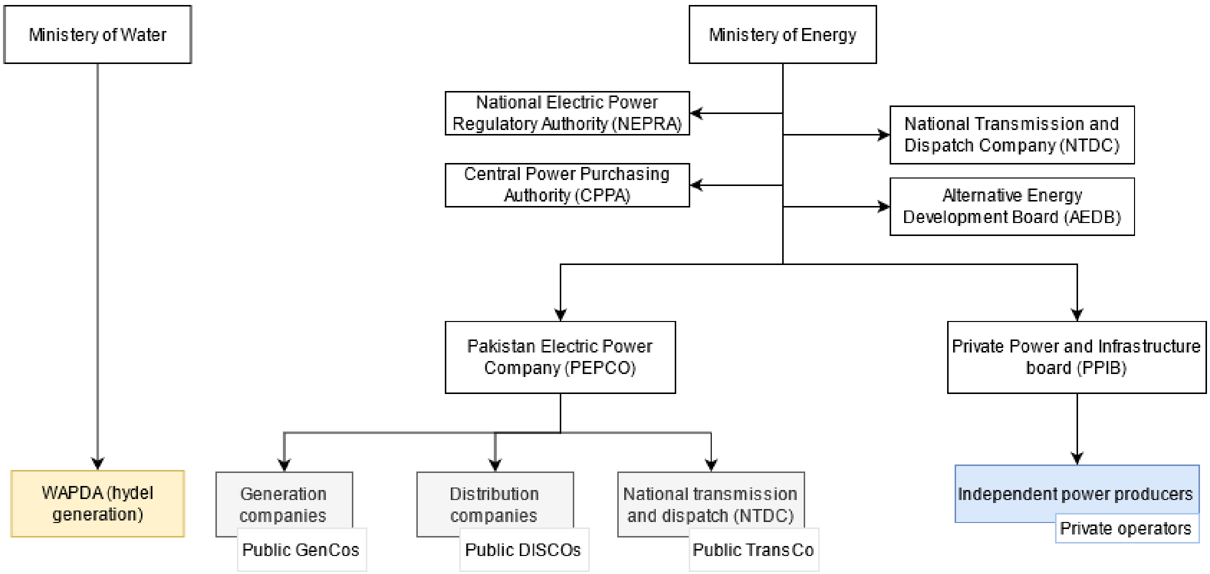

Figure 10: Organisational structure of the electricity market of Pakistan. The blue rectangle are the independent power producers that are in general financed by private investors. In the grey rectangle boxes the public utilities for distribution, transmission, and generation are presented. The two ministries are the political end-responsible for the functioning of the entities under supervision. The four white rectangle boxes below the ministry of Energy is respectively the market regulator (NEPRA), single buyer (CPPA), transmission system operator (NTDC), and a board to accelerate the energy transition (AEDB). The Water and Power Development Authority (WAPDA) is the utility that operate all public hydro power of Pakistan.

National Electric Power Regulatory Authority (NEPRA)

NEPRA is established in 1997 under the "Regulation of Generation, Transmission and Distribution of Electric Power Act" to develop and sustain a regulatory framework that ensures safe, reliable, efficient, and affordable electric power (Bacon 2019, 16). Also, NEPRA is responsible for transitioning from a protective monopoly service structure to a competitive environment (Bacon 2019, 16). NEPRA is bestowed with the following five tasks:

(I) It set transmission and distribution (T&D) loss targets for DISCOs (IMF 2019, 41).

(II) It grants licences for new generation capacity, transmission, and distribution investments (Bacon 2019, 16).

(III) It approves investment and power acquisition programs of the utility companies (Bacon 2019, 50)

(IV) It determines the cost-plus tariffs for solar and wind that form the basis for Power Purchasing Agreements (PPA). A PPA is essential for investors because it formalises against which price the generator sells its generated electricity.

(V) It calculates generation, transmission, and distribution tariffs on revenue required basis (Bacon 2019, 16). Revenue required basis means that NEPRA calculates what a generation, transmission or distribution company need to earn to meet full-cost recovery plus a reasonable profit. For distribution companies, this is called the Cost Recovery Tariff (CRT) that is coupled to certain performance expectations of the distribution company (Bacon 2019, 54). For generation companies, the NEPRA calculation is used as the basis for a PPA.

The NEPRA calculated electricity prices necessary for full-cost recovery is not the actual consumer tariff for electricity. The Minister of Energy determines the electricity price for consumers called the end-user tariff. This end-user tariff relates to the NEPRA determined tariff for the most efficient utility. The gap between the tariff arising from the revenue requirement for each DISCO and the end-user tariff is filled by a tariff differential subsidy (TDS) from the government (Bacon 2019, 54). The TDS is a strong driver of circular debt because the subsidy is paid with government spending.

Independent Power producers (IPPs)

Independent Power Producers are private investments in generation capacity that operate under a Power Production Agreement (PPA). All private investments are on a 'Take or Pay basis', and tariffs are determined in negotiation with NEPRA (NEPRA 2020, 38). In 2017, IPPs accounted for 42 percent (4 percent solar and wind) of the total generation capacity and all installed renewable energy (except hydro) (NEPRA 2020, 93).

Central Power Purchasing Authority (CPPA)

The Central Power Purchasing Authority (CPPA) is founded after the market operator responsibilities was separated from the NTDC. The Pakistan electricity sector is a single-buyer model where the CPPA is the single buyer (NEPRA 2020, 13). The CPPA buys all the electricity from the GENCOs, WAPDA and IPPs and sells it to the distribution companies (Bacon 2019, 19). CPPA also supplies electricity to the privatised vertically integrated K-electric. When the CPPA supplies electricity, the tariff charged to the DISCOs consist of the Cost Recovery Tariff (CRT) determined by NEPRA and the use of system charges of the Transmission Company (NEPRA 2020, 22). The distribution companies are required to pay the invoice of CPPA within a given time such that the CPPA can make necessary payments to the generation and transmission companies (NEPRA 2020, 22).

Public distribution companies (DISCOs)

The public distribution companies are responsible for electricity delivery from the transmission system to the consumer. There are a total of ten DISCOs for different parts of the country. Consumers can buy electricity at their local DISCO at a government-regulated tariff called the 'end-user tariff'. The DISCO is responsible for the administrative process, including bill collection. DISCOs are precarious because they buy electricity from the CPPA at the Cost Recovery Tariff (CRT) determined by NEPRA and sell it against the end-user tariff determined by the government. When there is a gap between the buying and selling price, which is currently the case, DISCOs cannot recover their full cost and either the government must provide subsidies or the DISCO accumulated debt. The latter increases circular debt. The circular debt problem is further aggravated by the under-collection of bills and T&D losses.

System performance

The collaboration of the actors in the electricity system did not result in the desired system performance of an affordable, reliable, and accessible electricity system. Electricity is expensive, many people still have no access to electricity, and load shedding still happens. Two drivers related to the organisational structure are (I) politized public institutions and (II) a risk-avoiding private sector. The public institutions have a low decision-making autonomy (Bacon 2019, 58). One of the most important aspects is the tariff setting authority that lies with the Ministry. This keeps the electricity sector prone to political opportunism and prevents market stabilisation and a strong and independent regulator. Secondly, private investors are reluctant to take risks in Pakistan's electricity market and pass these on to the government. Exchange rate risks, fuel price risk, fuel supply risk, inflation risk and demand risk are all hedged in the Power Purchasing Agreement. Due to the indebtedness of the public entities, they cannot invest themselves and accept the term of private parties.

3.4. Pakistan's electricity market in crisis

Before taking a closer look and separate drivers of circular debt, it is essential to look at the bigger picture of the current crisis. Pakistan has a general government gross debt of 87.2 percent to GDP, a deficit on the account balance of 13.42 percent, and a fiscal deficit of 8 percent at the end of 2020 (IMF, n.d.). This excess of spending and net importing is called a twin deficit and means that

Pakistan is lending from the rest of the world. These deficit numbers are high compared to the debt burden capacity of Pakistan[9]. Sustaining a twin deficit over the long run increases the risk of currency devaluation, which puts off investors and increases fuel prices. For Pakistan, which borrows foreign currencies, devaluation means that outstanding debt becomes harder to pay back, enlarging the risk of a currency crisis with grave economic and social consequences.

A driver of this government's debt is the electricity sector that relies on subsidies to stay afloat. Table 6 shows the government's claimed and paid (released) subsidy over FY 2019-20. The released payment is added to the government deficit, and the unpaid deficit is added to the electricity sector's total circular debt, which totals PKR 2,306 bln. Rupees (14.80 bln. Dollars) or 5.36 percent to GDP (2019 GDP) or 41 percent of tax receipt (IMF, n.d.).

Table 6: Subsidy FY 2019-20 (NEPRA, 2021)

	Subsidy FY 2019-20 (in Bln. Rs.)		Unpaid (bln. Rs.)
	Claim	Released	
Tariff Differential subsidy (TDS)	251	177	74
Other	66	5	61
Total subsidies DISCOs	317	182	135

The large subsidy payment with the already high public deficit and low tax income is unsustainable for Pakistan. To mitigate the circular debt crisis, multilateral funds[10] such as the International Monetary Fund (IMF) talk to the GoP to initiate reforms in exchange for debt restructuring.

3.4.1. Drivers of circular debt in Pakistan

Circular debt is a cash shortfall within the distribution companies that spread throughout the value chain. It tends to look like a "vicious circle" without a proper solution. The cash shortfall results from: (i) subsidy payment arrears by the government, and (ii) a mismatch between full-cost recovery and revenues realised by the DISCOs.

First, the cause of the subsidy payment arrears by the government is rooted in the retail pricing approach of Pakistan. In this approach the cost recovery tariff is estimated by the market regulator NEPRA, and the end-user tariff is determined by the Ministry of Energy. The end-user tariff is the actual price consumers pay for their electricity to the DISCOs. The difference between the end-user tariff (what consumers actually pay) and NEPRA's cost recovery tariff is filled with subsidies by the government called the 'Tariff Differential Subsidy' (TDS). However, the GoP cannot pay the full subsidy due to the precarious financial situation as discussed above, resulting in a payment arrear towards the DISCOs.

The second reason for debt accumulation is the mismatch between NEPRA's cost recovery tariff and the actual revenue needed to cover all the costs. The actual tariff needed to cover all costs is called the full-cost recovery tariff. NEPRA considers three main elements for the calculation of the CRT: (i) electricity procurement cost, (ii) transmission cost with limited losses, and (iii) 100% bill recovery. However, in reality, DISCOs' have lower bill recovery levels and higher transmission losses. The costs that are higher than prescribed in NEPRA's cost recovery tariff are unsubsidised, increasing the debt of DISCOs. Figure 11 provides a schematic overview of the reasons for revenue shortfall at the DISCOs.

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[9] Debt burden capacity is low in Pakistan due to large informal sector and low tax payment. The total revenue receipts in FY2019-20 were PKR 5,504 billion Rupees (35 billion US Dollar) (government of Pakistan Finance Division, 2021).

[10] Coordinated by the IMF, the World Bank together with the Asian Development Bank and the Japan International Cooperation Agency (Bacon, p20, 2019)

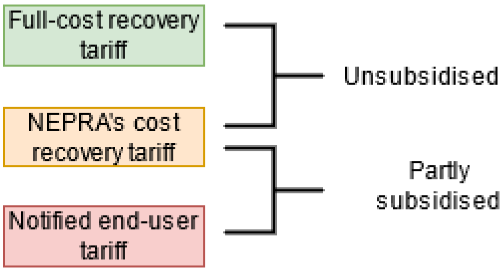

Figure 11: The subsidy arrear by the government is the result of inability to pay subsidy surfacing from the mismatch between NEPRA's cost recovery tariff (orange) and the GoP regulated end-user tariff (red). The second reason for debt accumulation at DISCOs is the result of a mismatch between the full-cost recovery tariff (green) and NEPRA's cost recovery tariff (yellow).

The drivers for the high tariff differential subsidy payments and resulting payment arrear are (i) inefficient and expensive electricity production and (ii) the formula to calculate NEPRA's cost recovery tariff. The drivers for the mismatch between full-cost recovery and the revenues realised by the DISCOs are (a) transmission and distribution losses and (b) non-payment of bills. Figure 12 provide an overview of how the drivers are related to each other.

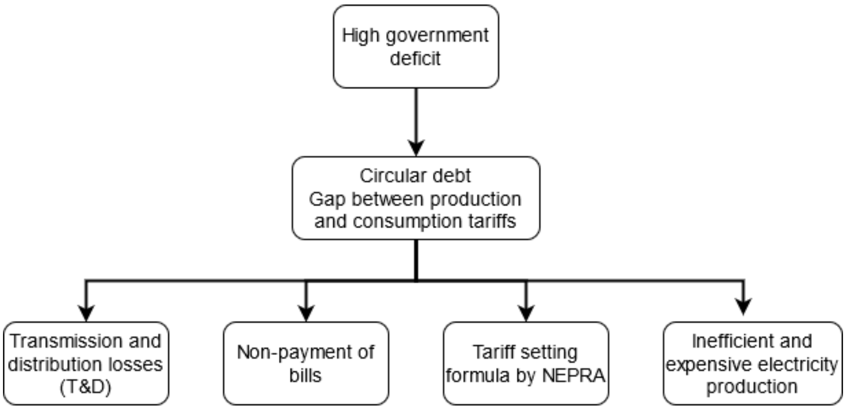

Figure 12: The flow chart presents the hierarchy of challenges in the circular debt crisis of Pakistan. The high government deficit leads to (i) subsidy payment arrears by the government, and (ii) a mismatch between full-cost recovery and revenues realised by the distribution companies which results in circular debt. Then circular debt is aggravated by four challenges: (1) transmission and distribution losses, (2) non-payment of bills, (3) tariff setting formula by NEPRA, and (4) inefficient and expensive electricity production. The focus of this research is on inefficient and expensive electricity production.

The inefficient and expensive electricity production is discussed in more detail because this is the central focus of the thesis. Also, the tariff setting formula is discussed in more detail as this is essential knowledge for linking the model results on contracted market price with circular debt. Information on the other two drivers of circular debt is presented in appendix N.

Tariff setting formula by NEPRA

For the calculation of the Tariff Differential Subsidy (TDS), the following decomposition is used:

$$(1) \qquad TDS = CRT - Notified\ tariff$$

Eq. (1) defines the Tariff Differential Subsidy (TDS) as the difference between the Cost Recovery Tariff (CRT) determined by NEPRA and the end-user tariff (what consumer pay) determined by the Ministry of Energy. The notified tariff is a result of a political decision-making process[11]. The Cost Recovery Tariff (CRT) considers (I) cost of power procured by CPPA, (II) reasonable assessed T&D losses, (III) 100 percent bill collection, (IV) use of system charges, (V) distribution margin and (VI) other costs (Bacon 2019, 34). Note that the Cost Recovery Tariff (CRT) is an estimate of NEPRA but is not the actually reported tariff needed for DISCOs to reach full-cost recovery. Therefore, debt accumulation by DISCOs is defined as:

$$(2) \qquad Debt\ Disco = Unpaid\ TDS + above\ CRT\ costs$$

Eq. (2) shows two sources of debt accumulation: unpaid TDS and above CRT costs. The unpaid TDS for FY2019-20, presented in Table 6, differs every year depending on a political decision-making process. The higher CRT costs can result from (I) higher T&D losses than the NEPRA target rate or (II) lower bill collection than the target rate. For example, the bill collection of DISCOs is not 100 percent, but the CRT calculation assumes it to be (Bacon 2019, 34).

Inefficient and expensive electricity production

To understand why the current electricity mix is so inefficient and expensive, we need to assess the history ranging back to 1994. During the mid-’90s, the Pakistan Government's policies favoured thermal powerplant development over VRE or hydro (ADB, 2019). Between 1994 and 2020, the share of hydro reduced from more than 80% to only 25%. In the same period, thermal increased its share to 65% (NEPRA 2020, 93). This rise in thermal energy production makes Pakistan short of indigenous oil and gas reserves, reliant on imported fossil fuel and vulnerable to a balance of payment crisis (ADB, 2019).

The currently high share of thermal originates from the 1994 National Power Policy that sought private investment in a reaction to power shortage and a call from multilateral institutions to open the economy for private investment (Bacon 2019, 14). The policy encompassed favourable standardised conditions for private investors. Due to the power shortages, the implementation of the policy appreciated oil-based powerplants over other technology because of their short manufacturing time (ADB, p10, 2019).

The PPAs that were negotiated with Independent Power Producers (IPPs) at that time were feed-in tariffs that guarantee a fixed return over the lifetime of a powerplant regardless of the efficiency and performance of the powerplant (Bacon 2019, 15). Also, the terms in the PPA effectively put the exchange rate risks, inflation risk, price fluctuating risk of raw materials, and fuel supply risks at the government (Bacon 2019, 14).

This short-term solution to solve the power shortage has long-lasting consequences. It started with an increase in oil prices from 16 dollars a barrel in 1994 to 38 dollars a barrel in 2004 which aggravated the Pakistan Rupee's depreciation after international opposition against nuclear tests in 1998. Prices for oil-based electricity skyrocketed, but the government hands were tied and obliged by the PPAs to supply fuel and buy the expensive electricity. This situation led to a currency crisis which put Pakistan on the brink of sovereign default. To leave the precarious situation, the GoP agreed to an IMF reform package that, in exchange, rescheduled their debt (Bacon 2019, 16). To meet the reforms, Pakistan unbundled WAPDA and established a single buyer market structure.

After the IMF bail-out, a period of relative calm emerged. The 2002 update of the power policy removed the troubling guarantee for the GoP to supply fuel to generators. In 2003 the AEDB was established to promote renewable energy, and K-electric was privatised in 2005.

[11] The tariff for residential consumer is differentiated in Increasing Block Tariffs (IBT) which means that households with low consumption pay less per kWh than households using more electricity (Bacon, P34, 2019)

In 2011, the energy sector slide-off again after the IPPs threatened to call sovereign guarantees because of non-payment (Bacon 2019, 18). The reasons for the non-payment were along the same lines as in the current circular debt crisis. In the years 2011-2013, there were severe power outages that led to violent protests. The Pakistan government, which opposed international assisted had no choice but to accept a new 5.3-billion-dollar loan from the IMF in 2013. With the loan, Pakistan cleared 4.8 billion dollars of circular debt. The GoP launched a new power policy with the same aim as in 1992: unbundling, privatisation, and competition (Bacon 2019, 20).

After the 2013 IMF bail-out, the GoP started with high expectations but made little progression. Under political pressure for the 2018 election, all privatisation plans were put in the fridge while the Tariff Differentiated Subsidies (TDS) kept pouring into the electricity market to fill the gap between CRT and End-user tariff (Bacon 2019, 23). Attempts were made to prevent a new circular debt crisis, but they crumbled under policy drift.

During this turbulent history, the electricity market of today was shaped. Decisions made over decades created the current thermal heavy electricity mix, unfavourable take-or-pay cost plus PPAs, high production costs, low consumer tariffs, poor transmission network quality, and lack of incentive to efficiently produce electricity.

4. AGENT-BASED MODEL CONCEPTUALISATION

The previous chapters described the viewpoint on the two most important actors of the system. This chapter continues with the conceptualisation of the electricity system towards a full conceptualized investment model. The real-world system described in the previous chapters is demarcated towards an investment model including the market regulator NEPRA, investors, and the electricity market. This high-level model allows the possibility of testing different behavioural scenarios and recording the effect on the contracted market price of electricity and the generation mix. The acquired information on the contracted market price can be linked with the direction of the circular debt crisis. The step-by-step demarcation of the full system into a high-level investment model is explained in Appendix B.

4.1. High-level conceptualisation

Figure 13 shows an input-output model of the investment model. The basic principle of the investment model is a three-step cycle: (I) NEPRA determines a PPA-tariff for each generation alternative, (II) investors calculate the net present value for each generation alternative based on their discount rate and invest in a generation type with a positive business case, (III) all investments together in the electricity market update the two key performance indicators: contracted market price and the generation mix. The model starts in 2020 and repeats the model cycle each year for 25-years.

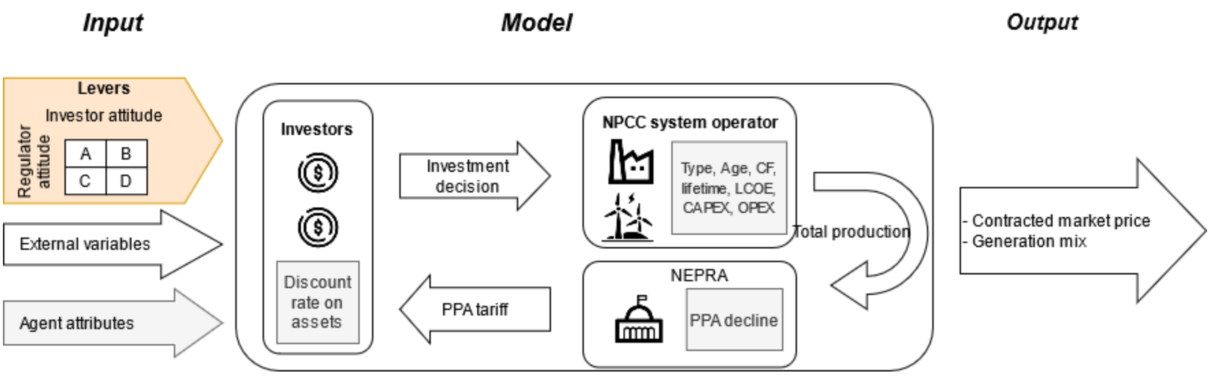

Figure 13: Input-output diagram of Pakistan's investment model. The orange input represents the 2x2 matrix based on the model levers that constitution the four behavioural scenarios. The white input arrow represents the external input variables. The grey arrow represents the agent attributes which are shown in the grey boxes in the model environment. The model has a three-step cycle: (I) NEPRA determines a PPA-tariff for each generation alternative, (II) investors calculate the net present value for each generation alternative, (III) all investments together in the electricity market update the two key performance indicators. The model's output is the key performance indicators 'contracted market price' and 'generation mix'.

Figure 14 presents the XLRM diagram with all model variables. The XLRM diagram shows the impact of the behavioural strategies (left) on the Key Performance Indicators (right), given the external variables (top) and the relations in the model (square) (Nikolic et al., 2019). The set of external variables are variables the ABM model uses for its calculations but are indifferent to the model dynamics. The external variables are tested on sensitivity in chapter 7. The behavioural levers are manipulated for each intervention scenario. Finally, the key performance indicators measure the output of the model. In the remainder of this chapter, the Pakistan investment model is explained.

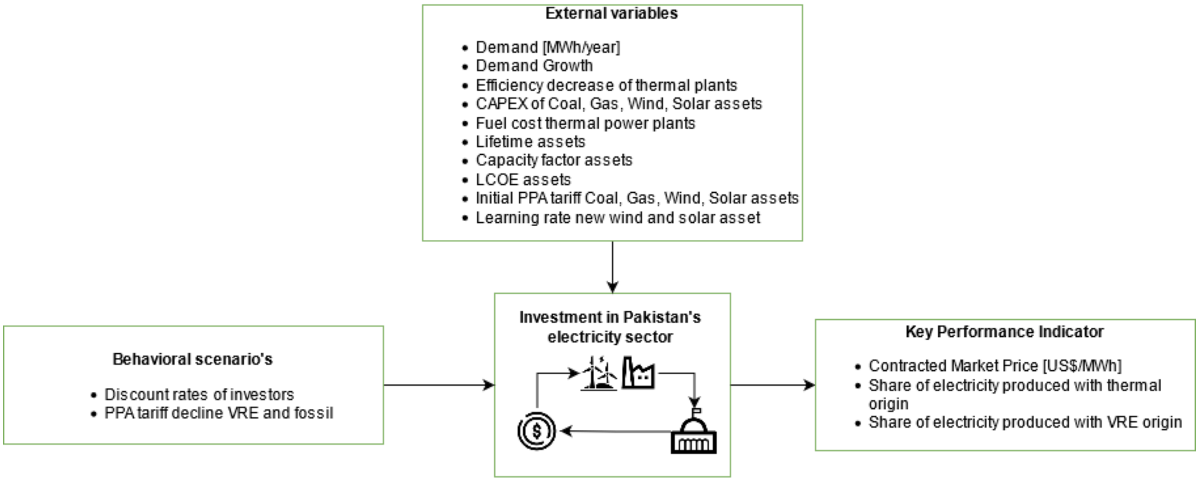

Figure 14: This XLRM diagram represents the conceptual agent-based model view by showing the model levers (left), the exogenous variables (top), and the Key Performance Indicator (right). The square box shows the relationship in the model between the market regulator, investors, and the power plants. Adapted from Nikolic et al., 2019.

4.2. Behavioural levers

Behavioural levers are changes in behaviour within the sphere of influence of investors and the market regulator that impact the key performance indicators. The following levers are included:

- Discount rate of investors
- PPA tariff reduction rate

In the agent-based investment model the discount rate of investors is equal to the investors' long-term risk expectation for investments (Kraan et al., 2018). In broader financial terms discount value is equal to the investors' expression for time value of the invested money. When the discount rate increases an investor expects that the future earnings need to be higher to offset the risks associated with the investment. If the discount value declines the investor the risks associated with the investment declines. The discount value is the only differentiator for risk outlook of investors.

A PPA tariff is the agreed price between the market regulator and the private generator to produce one kWh. At model initialisation all four generation alternatives have a PPA price. The PPA price is used to calculate the revenue side of the NPV calculation. Every year the PPA price declines with the PPA tariff reduction rate. This means that new investments are offered a lower price per produced kWh.

4.3. Performance metrics

The two key performance indicators for the model are *the contracted market price* and *the generation mix.* With information on both metrics, the effectiveness of policies can be evaluated over time. Furthermore, the policy levers provide information necessary to answer the main research question on the effect of variable renewable energy investment on circular debt.

4.4. Relationship within the model

In this section, the settings of the model are explained. First, the model boundaries are explained. Secondly, the two most important actors are analysed. Lastly, two critical model procedures are discussed.

4.4.1. Model boundaries

Time frame

The investment model simulates 25 years, starting in 2020 and ending in 2045. For an electricity sector transition, this is a relatively short time window because the average coal powerplant has a lifetime of 34 years. However, the modelling forecast of the government performed by the National Transmission and Distribution Company (NTDC) has also a time window until 2045. Therefore, it is assumed that the government maximum horizon for policy implementation is approximately 25 years.

The scale of the model

The amount of assets in the model is scaled by normalizing the generation capacity of each generation alternative. The initial amount of assets equals 58, while in reality, this is more than 130.

Investment options

Investors have an investment choice limited to coal, gas, solar and wind.

4.4.2. Portraying investors and the market regulator

This section takes a closer look at the two actors decisive for new investments: NEPRA and investors. Together both actors have a central role in the Agent-Based investment model. Therefore, their behaviour is examined in-depth, after which they are conceptualised for implementation in the next section.

NEPRA: at the helm of the future electricity mix

Pakistan is a centrally planned electricity sector that does not behave according to the rules of the market. In a competitive wholesale market, investors have an expectation of the future benefits of an investment and invest in new generation capacity when an investment has a positive business case. The largest influence from the government in a competitive market that is favourable to a particular investment is the availability of subsidies. In Pakistan, however, the revenue side for a new generation facility is entirely determined by the decision of NEPRA about the PPA tariff (personal communication, June 17 2021, Appendix C.5). The tariffs determined by NEPRA for the different generation types differ drastically. For example, a gas powerplant got in 2019 a PPA tariff of almost 90 $US/MWh while a recent solar project received only 30 US$/MWh (see appendix F). Both projects are executed, which means that the PPA tariffs are justifiable for NEPRA. Why it is precisely justifiably is hard to decompose because of the untransparent political process driving this decision. The point remains that under the existing circumstances, these tariff differences are acceptable.

The PPA tariff determination is a negotiation between a project developer[12] and NEPRA. In these negotiations, NEPRA builds on an international benchmarking of electricity tariffs, national and international, information by the transmission system operator (NTDC) on the cost of grid connection, and the project developers proposal. Aside from the official price determination, there is ample room for lobbying and political influence in the untransparent tariff determination process. In Pakistan, this lobbying power and political influence are reserved for influential stakeholders. Currently, these are represented by incumbent actors from the thermal business. This means that renewable energy investors have no lobbying power and are entirely left to the decisions made by NEPRA (personal communication, June 17 2021, Appendix C.5).

The process that determines new PPA tariffs draw heavily on the expectation by NEPRA about the future of the electricity market. Similar to the expectation for an investor in a competitive market is central in their investments. A recent report by the National Transmission and Despatch Company (NTDC) provide an expectation of the future electricity market (NTDC, 2020). The report executed a modelling study in the same modelling software as the recent World Bank study on VRE integration in Pakistan (World Bank, 2020b). Comparison of both models shows on the topic

[12] A project developer is the entity leading and in charge of building the new generation capacity. Investors are typically banks that finance the project developer's electricity generation project.

of VRE integration large differences. Same electricity market, same model software, but different assumptions lead to significantly other results. Therefore, the conclusion is drawn that the assumptions in the NTDC model are a mirror for the PPA determination strategy by NEPRA. Put differently, the predicted development of the generation mix towards 2047 is also a prediction of the PPA tariffs for years to come. Both public entities operate under the supervision of the national government, which enforce the assumption that NEPRA takes over the expectations by the NTDC.

The NTDC (2020, 67) discuss in the power system planning report that variable renewable energy will quickly become the cheapest form of electricity. They argue that VRE can outcompete other fossil fuel technologies and reduce dependency on expensive imported fuels. According to the report, the extent to which VRE could replace fossil fuel depends strongly on: (I) the ability of the electricity grid to sustain variability of electricity production by VRE sources and (II) the cost of operating coal powerplants fuelled with domestic thar coal (NTDC, 2020).

Despite the expectation that VRE becomes the least-cost option, the model results show a 33% share for hydro, 20% share for gas, and a strong rise of indigenous coal powerplants, up to 36% in 2047. The coal increase is largely explained by the sharp decline in fuel cost of domestic thar coal (NTDC 2020, 27). VRE initially rise sharply from 3% in 2020 to 23% in 2030, influenced by central government climate ambitions. However, after 2030 the share of VRE declines to 15% by the end of 2047 (NTDC 2020, 27).

The World Bank (2020b) study in the same result shows a different VRE increase picture. In their results, in all but one scenario, the share of VRE increases after 2030, from ~30% in 2030 to shares between 40 – 50% 2040 (The World Bank 2020b, 197). Which model input parameters results in such divergent results? A strong influencer is a different expectation about the future price for domestic thar coal. The NTDC expect that the price for imported thar coal will drop suddenly from a factor 0.99 in 2029 to 0.71 in 2030, which remains around the same value until 2047. The World Bank (2020b) has not published their domestic thar coal outlook. However, the scenario '*no further VRE growth*' that includes a sharp rise of domestic coal is marked as the most expensive of all scenarios. This indicates that The World Bank's assumes that burning domestic thar coal is far more expensive than expected by NTDC.

Another interesting assumption in both the World Bank (2020b) as the NTDC (2020) report is the rather modest learning curve of 3,6% and 1% for solar and wind, respectively (NTDC 2020, 67; The World Bank 2020b, 270). In comparison, the historical learning curve (2010 -2019) is 21% and 5.5% for solar and wind, respectively, according to our world in data (ourworldindata, 2020).

The International Renewable Energy Agency [IRENA] (2018) expect that worldwide, 85% of electricity will be produced by renewable sources in 2050. This makes the far higher PPA tariffs awarded to fossil fuel projects by NEPRA inexplainable with only economic arguments. There are also (geo)political and social dynamics that defy economic rationality and promote the incumbent energy sources. Vox (2020) argues that coal is kept alive in centrally planned electricity markets by path dependence, political influence, and distorted markets. Vox (2020) bases themselves on the observation that countries with more competition have less coal and countries with more monopolistic utilities, more lobbying by fossil fuel industry, and more socio-economic resistance from areas depending on fossil fuel power plants for local revenue have more coal (Vox, 2020).

To conclude, NEPRA determines the PPA prices for future power plants and steers the future energy mix of Pakistan. Even though the current differences in PPA tariffs among generation alternatives are economically not rational, they are nevertheless awarded to new powerplants. Regardless of the exact decomposition of factors that explain the difference in PPA tariffs, it is the reality for the Pakistan electricity market. Therefore, the leading principle for the model is that there will remain a privileged position for thermal electricity generation over VRE.

Investors: a wide range of objectives and approaches

NEPRA steers the future electricity mix by handing out PPA tariffs to investors. Investors steer the future generation mix by their decision to invest in a particular generation alternative. Investors decide to invest in a particular generation type by a heterogeneous set of considerations. This is not limited to considerations involving investors specialism, the business case of generation alternatives, geopolitical pressure, taxation, the possibility to lobby for better PPA tariffs, and political support during the operational time of an asset. Every investor makes a different trade-off on these considerations, resulting in different business cases (personal communication, June 17 2021, Appendix C.5). The different investors are separated in this model according to a bell curve distribution, also used in the diffusion of innovation theory (Rogers, 1962). In the bell curve of the diffusion of innovation theory, there are two large groups, early majority and late majority, in the investment model, respectively progressive investors in VRE and conservative investors in VRE. The progressive investors have a more positive view on investing in VRE because they point towards the rapidly declining cost of VRE, expectation to acquire a large market share, and the importance of VRE to reach the climate goals (personal communication, June 17 2021, Appendix C.5). Progressive investors expect that the government will steer towards VRE friendly policy which includes more profitable PPA tariffs than currently handed out (personal communication, June 17 2021, Appendix C.5). If the market picks up with better PPA tariffs, the initial investments provided a head start for the investors (personal communication, June 17 2021, Appendix C.5). Conservative investors, on the other hand, have a large interest in the status quo and remain strong investors in fossil-fuelled thermal powerplants. The third group of investors are early adopters. In the model, this third group is translated to development finance institutions (DFI's) that made it their mission to boost early investment in VRE and accept the high uncertainty associated with being one of the first renewable investors in a country.

4.4.3. Conceptual representation of investors

The previous section showed the great variety of investors and their large set of diffuse, irrational, and unclear investment criteria, making them challenging to capture in a conceptual model. In Agent-Based models based on the liberalised electricity market, the conceptualisation can, to a great extent, be based on the market orientated assumption (Kraan et al., 2017). However, with the system of lifetime guaranteed cost-plus PPA tariffs, Pakistan's electricity market triggers a whole different set of investment logic.

A conceptual view on investors

The three types of investors are characterised as follow:

- Development Finance Institutions
    - Relative low investment capacity
    - High acceptance of risk for VRE projects, and therefore a lower than average discount rate.
    - Investment restrictions on thermal powerplants
- Conservative private investors
    - Normal investment capacity
    - Negative attitude towards VRE investment and have therefore higher discount rate in their renewable NPV calculations
    - Positive attitude towards fossil fuel investments
    - No investment restrictions
- Progressive private investors
    - Normal investment capacity
    - Has no bias towards either generation alternative
    - No investment restrictions

A conceptual view on NEPRA

NEPRA is conceptualized with the most recent PPA tariffs as a reference point for future PPA tariffs. Every year the PPA tariff for new generation capacity declines. This is based on the expectation that over time the economically irrational attitude of awarding high PPA tariffs to expensive thermal generation capacity will reduce because of (I) pressure by the international community to cut carbon emissions, (II) an increasing share of VRE increase the lobbying power of VRE investments to divert the pro-fossil fuel bias in PPA determination and (III) pressure by the international group of lenders to reduce electricity tariffs. NEPRA issues PPA tariffs for new generation capacity up until the point that generation capacity surpasses demand. The extra cost for implementing VRE generation assets is added to the business case in the form of profile cost.

4.4.4. Critical procedure I: PPA tariff determination

Observation: When looking at the LCOE prices of VRE, they are much cheaper than other sources. They are not built massively in Pakistan due to path dependence, political influence, and distorted market. There are still investments made in coal and gas power plants. However economically irrational, it still happens.

The PPA tariffs slowly reduce with a fixed percentage each year to model this irrationality and account for the increasing awareness that VRE is necessary and cheaper.

4.4.5. Critical procedure II: Investment decision

The investment decisions are made in multiple rounds where investors make decisions in random order based on the NPV score. To model the heterogeneity of decisions, an investor does not automatically invest in the generation asset with the highest NPV. Instead, the Investors award a change proportional to the NPV value. The NPV with the highest value has the biggest chance of construction, and the lowest positive NPV has the lowest construction chance.

5. BEHAVIOURAL INTERVENTIONS

This chapter discusses the design of behavioural scenarios. The experiments revolve around the behaviour of the market regulator and investors.

First, the logic behind the parameter settings of both actors is provided. Then the experimental setup is discussed.

5.1 Market regulator

The market regulator of Pakistan is NEPRA. This public entity is entrusted with two key tasks (i) the approval of new PPAs for investors (Bacon 2019, 50) (ii) identifies possible projects for investors to react upon (personal communication, June 17 2021, Appendix C.5). This means that the NEPRA determines to a large extent both the business case and the available project for investors. The establishment of new PPA prices for investors and picking available projects is a highly dispersed process. The official aim of NEPRA is to strike a balance between the different goals of affordability, reliability and accessibility of electricity. However, because the decision is made by a monopolistic and governmental influenced public entity, the final decision is influenced by a manner other factors. Especially, the political influence and strong influence of incumbent stakeholders make decision-making incoherent. The high bureaucracy of the decision-making also adds to irrational decision-making because processes proceed slowly.

The factors mentioned above make the long-term behaviour of the market regulator NEPRA challenging to predict in the future. Therefore, multiple plausible futures regarding tariff setting by NEPRA are tested. By, doing this insight is gained in the sensitivity of NEPRAs behaviour for circular debt. The large set of quantitative variables that shape tariff propositions for new projects are impossible to conceptualise reliable. Therefore, a stylistic approach is chosen where the attitude by the NEPRA is altered between conservative and progressive regarding favourable PPA tariffs for renewable energy projects.

Figure 15 shows the experimental settings used for a progressive or conservative NEPRA.

Figure 15: The experiment settings for conservative or progressive NEPRA.

A conservative NEPRA slowly (1%) decline their tariffs for new fossil fuel investments. When the positive net present value for fossil fuel powerplants decline or even becomes negative, the model's investments also reduce. In the model, the efficiency increase of thermal powerplants or fuel price alteration is not considered. A lower PPA tariff directly influences the chance a thermal powerplant is built. A conservative NEPRA quickly (3%) reduce the PPA tariff for renewable energy. This means that the PPA tariffs will remain less attractive for investors. A progressive NEPRA flip the dynamic, fossil fuel business cases diminish faster, and VRE business cases become more interesting for investors.

5.2 Investor

As discussed in 4.4.2, investors are divided according to the technology adoption lifecycle into three types: Development Finance Institutions, progressive investors, and conservative investors. These investors make investment decisions based on the business case and the potential to do more projects in the future. An investment expert told during an interview that they make significant investments before receiving a PPA proposal of NEPRA (personal communication, June 17 2021, Appendix C.5). In one instance, it took four years. The investment expert explained that their company was willing to muster the stamina while many other investors were unwilling to go this length. This underlines that investors have different risk assessments.

Figure 16 shows the experimental settings used for a market attitude regarding renewable energy of a follower (conservative) or a front runner (progressive).

Figure 16: The experimental setting for investors. On the left-hand side, the settings for investors as a follower, on the right side-hand side, the settings for investors as a front runner

5.3. Behavioural experimental setup

Three types of private investors in generation capacity are distinguished: Development Finance Institutions (DFIs), progressive and conservative investors. They act as front runners or followers in the energy transition. Furthermore, the market regulator NEPRA can show a progressive or conservation attitude towards renewable energy. Table 7 presents the four behavioural scenarios tested in the agent-based investment model during 25-year of the energy transition.

Table 7: 2x2 matrix shows the behavioural scenarios of market regulators and investors, resulting in four scenarios (A, B, C, D). The vertical axis shows the price-setting behaviour of the market regulator: progressive or conservative regarding VRE generation. The horizontal axis shows the attitude of investors: followers or front runners in the energy transition.

		Investor's attitude	
		Followers	Front runner
Market regulator renewable energy price-setting	Progressive	A	B
	Conservative	C	D

5.3.1. Model levers

- Discount value (investors)
- PPA decline (market regulator)

The model levers are explained in section 4.2.2.

6. MODEL IMPLEMENTATION AND VERIFICATION

6.1. Model implementation

The conceptualised electricity market is implemented in the Netlogo software. First, the input data is collected for the model calculation on the current assets in the electricity market (Appendix E), data necessary for NPV calculations (Appendix F), input on VRE profile cost and VRE learning rate (both appendix G). Secondly, the model dynamic is formulated in a model narrative (appendix H) based on the conceptualisation presented in Ch. 5 and expert interviews (appendix C).

Figure 17 shows a visual representation of the agent-based investment model. The large square area in the middle is the monitor that represents the electricity market of Pakistan. White and green dots are initial assets, and red dots are newly built assets. At the top of this square three investors (pink, green, blue) and is the market regulator NEPRA (orange) presented.

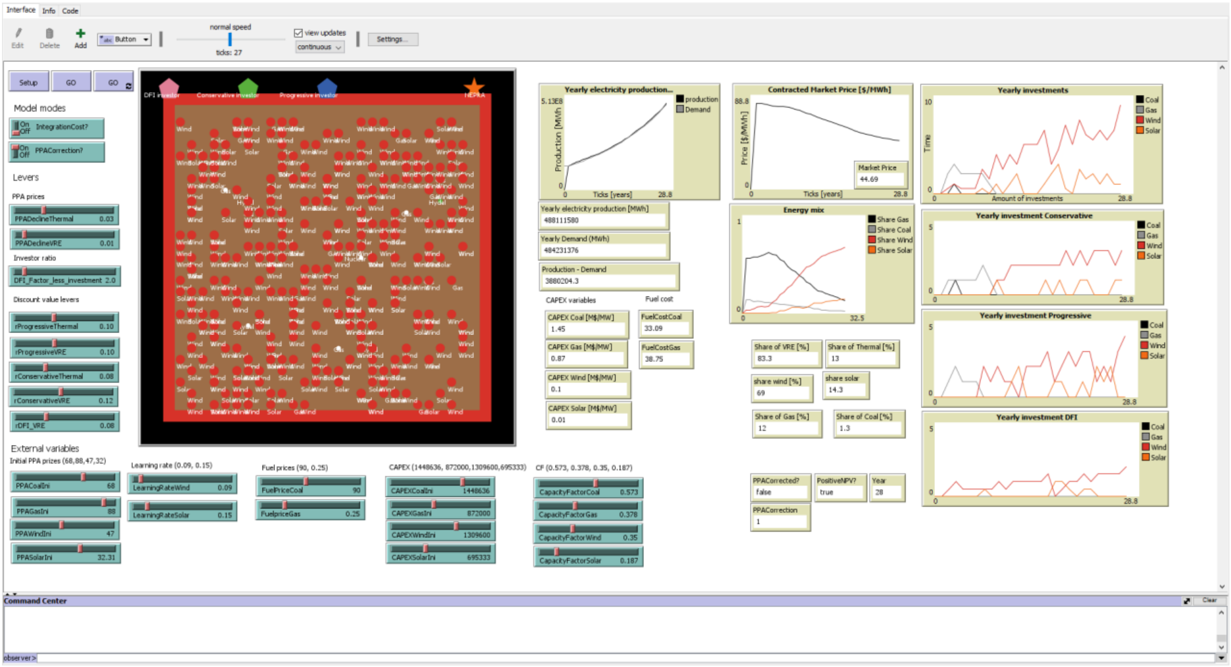

Figure 17: A visual representation of Pakistan electricity investment model.

Furthermore, on the left-hand side, the policy levers (in green) are represented as sliders. They are divided into four categories (from top to bottom):

- The PPA decline slider that represents the percentual reduction of the PPA tariff
- Two sliders show the learning rate of solar and wind
- One slider represents the factor that a DFI invests less than one of the other two investors
- The bottom four sliders are the sliders to change the discount rate of the different actors and the generation type.

At the right-hand side of the model, the output is visualised in yellow graphs and small blocks. The three graphs show the yearly electricity production (top left), contracted market price (top right), and the energy mix (bottom right). The three monitors directly beneath the yearly electricity production graph are numerical representations of the graph. Beneath that, there is a numerical representation of the CAPEX and fuel cost of the four investment types. Lastly, a numerical representation of the share of solar, wind, and total VRE in the electricity mix is provided at the right bottom corner.

6.2. Parametrisation

According to van Dam et al. (2013), parameterisation finds appropriate values for the model variables. The values for this model are derived from literature or expert interviews. Appendix I provide an overview of the parameter settings and the rationale. The electricity system is a complex adaptive system that contains large uncertainties when picking the correct parameter value. Potentially differences in initial parameter settings can drastically influence model behaviour and outcomes. The variables with large uncertainties or large influence on the model outcome are included in the scenario analysis in the next chapter.

6.3. Verification

The model is extensively tested to ensure that the conceptual model is correctly translated into an agent-based model. Three types of tests are executed: (i) recording and tracking agent behaviour, (ii) single-agent testing, and (iii) extreme value testing (Van Dam et al., 2013). Appendix L provides the details of the executed tests. Besides testing the final model version, also the model is tested during the construction. After these extreme tests, the modeller is provided with a comfortable confidence level that the model was built the right way. Therefore, it can be used in the next chapter to generate results.

7. RESULTS

This chapter aims to analyse the behavioural interventions formulated in chapter 5. Additionally, the chapter explores the sensitivity of the external model variables. Data for analysis is acquired by running different parameter settings in the agent-based model. For the execution, the integrated tool behaviour space in Netlogo is used. The output data is analysed using Python with the packages Matplotlib, Seaborn and Pandas.

7.1. Overview of scenarios

This study uses four behavioural experiments, which will be tested under different scenarios. The experiments cover the input variables for the agent-based model. Figure 18 (extensively discussed in Chapter 4) depicts the variable groups and their relation to the agent-based model.

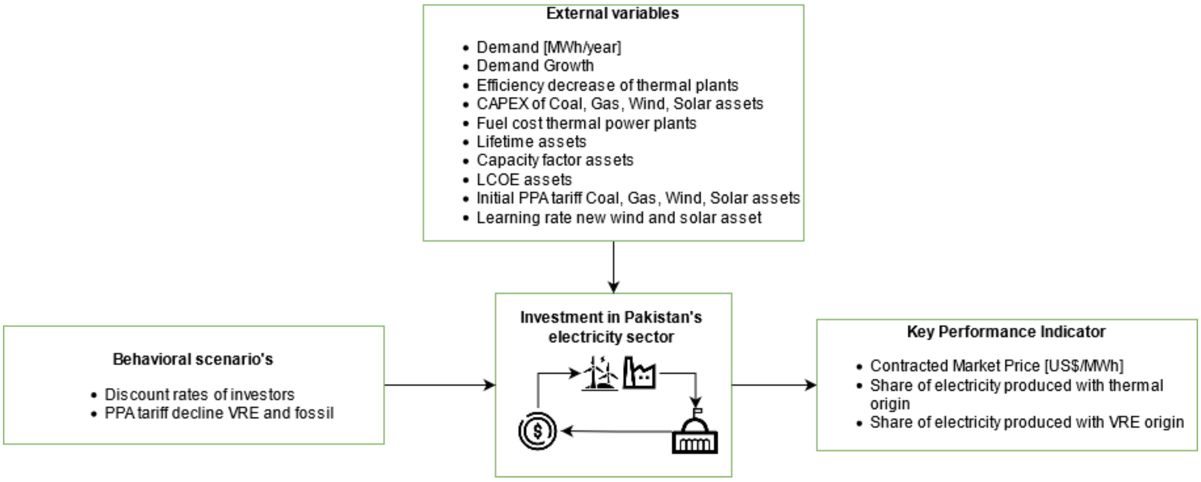

Figure 18: This XLRM diagram represents the conceptual agent-based model view by showing the model levers (left), the exogenous variables (top), and the Key Performance Indicator (right). The square box shows the relationship in the model between the market regulator, investors, and the power plants. Adapted from Nikolic et al., 2019.

First, the influence of the behavioural variables on the KPI's is analysed. Table 8 shows the experimental settings for these behavioural experiments. The impact on the model outcome is measured with the Key Performance Indicators shown on the right side of Figure 18.

After the behavioural experiments, six scenario experiments are performed that explore the sensitivity of the KPI's when varying the external variables. The exploration is crucial for this complex adaptive system because the model contains many external variables with an uncertain initial parameterisation and unpredictable value development over the 25-year period. The six experiments only cover the external variables that both have a high impact on the model outcome as well as a high uncertainty concerning the initial parameter value and its future development. *Fuel price* is the most obvious external variable with high impact and high uncertainty: it influences the business case of thermal powerplants to a large extent, but at the same time, the future market price of fuel is impossible to predict. Section 7.3.1 explains in more detail the rationale why explicitly the external variables in the six scenarios are chosen.

Table 8: Overview of the performed experiments. Table includes the variables and values with which they are varied. The last column is the total number of replications for the total experiment.

Experiments	Variables	Values	Iterations
Behavioural	Discount VRE Progressive Discount Thermal progressive Discount VRE conservatives Discount thermal conservatives Discount VRE DFI PPA decline VRE PPA decline thermal	0.08 / 0.12 0.12 / 0.08 0.10 / 0.14 0.10 / 0.06 0.06 / 0.10 3% / 1% 1% / 3%	400
Scenario 1: fuel prices (OPEX)	Fuel price coal (US$/Ton) Fuel price gas	45.09 (-50%) – 180.36 (+50%) 0.125 (-50%) – 0.50 (+50%)	400
Scenario 2: CAPEX	CAPEX Coal in M$/MW CAPEX Gas CAPEX Wind CAPEX Solar	0.87 (-40%) – 2.03 (+40%) 0.52 (-40%) – 1.22 (+40%) 0.79 (-40%) - 1.80 (+40%) 0.42 (-40%) – 0.97 (+40%)	800
Scenario 3: PPA prices	PPA prices coal in US$/MW PPA price gas PPA price wind PPA price solar	54 (-20%) - 81 (+20%) 71 (-20%) – 106 (+20%) 38 (-20%) – 56 (+20%) 26 (-20%) – 38 (+20%)	800
Scenario 4: VRE cost reduction	Cost reduction wind Cost reduction solar	2%(Low),10%(Medium),18%(High) 2%(Low),10%(Medium),18%(High)	300
Scenario 5: Capacity factor assets	CF coal CF gas CF wind CF solar	46% (-20%) - 69 (+20%) 30% (-20%) - 45% (+20%) 28% (-20%) - 42% (+20%) 15% (-20%) - 22% (+20%)	800
Scenario 6: Integration cost	Integration cost	True/False	

7.2. Behavioural strategy

7.2.1 Design of strategies

The various behavioural experiments are run in four different parameter settings to research the effect of different investment and price-setting strategies on the market price and energy mix. Every parameter setting is run a hundred times. This brings the total to four hundred for the whole experiment. In these four parameter settings, the attitude of the market regulator towards renewable energy can only shift between conservative and progressive. The investors' attitude is varied between the risk perception of a front runner and a follower. This results in a 2x2 matrix with four scenarios; Table 9 depict this in greater detail. For a detailed rationale on the behavioural experiment design, please refer to chapter 5. The expectation is that the top left scenario (scenario A) and the bottom right (scenario D) bear the most extreme outcomes. The other two scenarios are opposing combinations of attitudes and produce results somewhere between scenarios A and B.

Scenario A is the scenario in which the government and investors together embrace the energy transition. In this scenario, the market regulator decreases the PPA prices on fossil fuel generation three times faster than that of VRE. This results in a strengthening of the VRE business case while weakening the business case for thermal powerplants. Simultaneously, investors attitude towards investing in VRE is favourable. The market conditions allow for lower risk expectations concerning renewable energy investments while the risk perception towards thermal alternatives grows. These changes in risk perceptions result in strengthening VRE business cases while weakening the thermal business case. Therefore, scenario A will most likely see the largest uptake of renewable energy.

Scenario D is the opposite of scenario A. In scenario D, market regulators and investors alike stay on the same track of relying on thermal sources for their electricity generation. This includes squeezing the business case of VRE by the market regulator and investors that are hesitant to invest in VRE. Scenario D will probably see the slowest uptake of VRE.

Table 9: A detailed design of the behavioural experiment. The experiment varies two levers on two settings; this results in a 2x2 matrix with four scenarios.

		Investor's attitude	
		Front runner	Follower
Regulator VRE price setting	Progressive	PPA fossil 3% PPA VRE 1% VRE progressive 0.08 Thermal progressive 0.12 VRE conservative 0.10 Thermal conservative 0.10 VRE DFI 0.06	PPA fossil 3% PPA VRE 1% VRE progressive 0.12 Thermal progressive 0.08 VRE conservative 0.14 Thermal conservative 0.06 VRE DFI 0.10
	Conservative	PPA fossil 1% PPA VRE 3% VRE progressive 0.08 Thermal progressive 0.12 VRE conservative 0.10 Thermal conservative 0.10 VRE DFI 0.06	PPA fossil 1% PPA VRE 3% VRE progressive 0.12 Thermal progressive 0.08 VRE conservative 0.14 Thermal conservative 0.06 VRE DFI 0.10

The effect of the different parameter settings in the scenarios is tested on the Key Performance Indicators. Those are contracted market price and the electricity mix. The contracted market price is the price the CPPA-G (single buyer entity) must pay on average per MWh. The electricity mix provided additional information on the share of renewable energy in the market and the dominance of generation alternatives.

7.2.2. Results behavioural strategies

Figure 20 shows the effect of the behavioural experiment on the contracted market price. The contracted market price gradually declines in all four scenarios because more efficient new ones replace older more expensive powerplants. The contracted market price reduction is the strongest for scenario A '*energy transition'* and weakest for scenario D *'status quo'*. Apparently, the scenario with the investment and price strategies favouring VRE alternatives result in the lowest contracted market prices. The opposite holds for scenario D, '*status quo'* that embraces for a much longer period the thermal energy of all four scenarios.

Scenario B '*renewable policy'* and C *'VRE push by investors'* lay within the boundaries set by the other two scenarios. Figure 20 illustrates what happens when the market regulator changes their price-setting strategy (green arrows) or the investment strategy change (orange arrows).

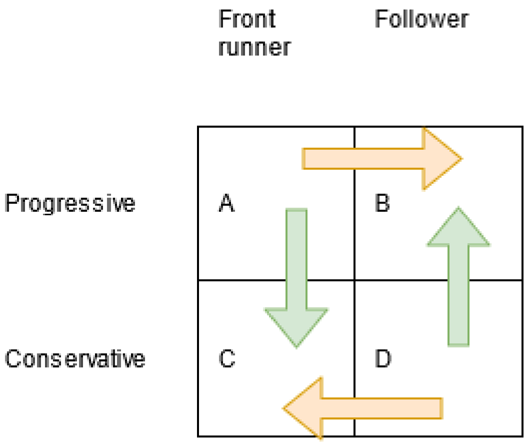

Figure 19: Changes in market price oriented from the two extreme scenarios A and D. The orange arrows represent the investors' investment strategy change. The green arrow represents the market regulator's price setting strategy change.

When the investment strategies change (orange arrows), the influence on the contracted market price is smaller than a change in the price-setting strategy by the market regulator (green arrows). The effect is visualized by the number of yearly investments for the four behavioural scenarios presents in Figure 22. On the horizontal axis (yellow arrows), the change in the number of investments is modest. The right-hand scenarios show more thermal investments, but the general behaviour remains the same. The vertical axis (green arrows) shows the difference in yearly investments if the market regulator changes its price-setting strategy. Looking vertically from scenario A to C and from B to D the investment behaviour totally changes. In scenario A, wind investment is the majority, while in scenario C, coal is the majority investment. The same dynamic is observed from scenarios B to D.

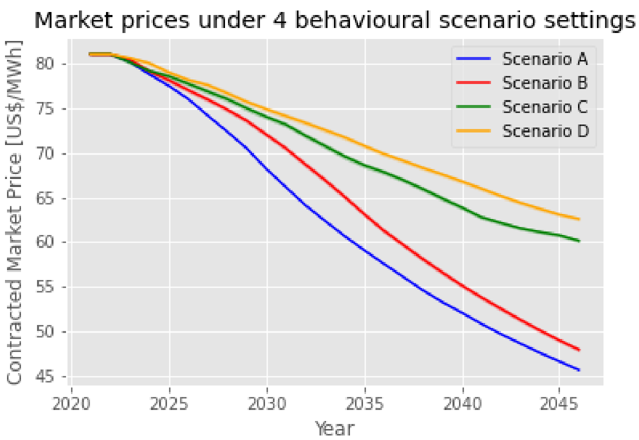

Figure 20: The contracted market price for the duration of the model in four scenarios. Scenario A and scenario D mark the boundary values for the contracted market price.

Figure 21 contains the same data as Figure 20, but it is depicted as a boxplot. The boxplot shows the distribution of the data. For all four scenarios, the interquartile range (difference between the third and first percentile) is narrow enough to conclude that the differences between the scenarios are significant.

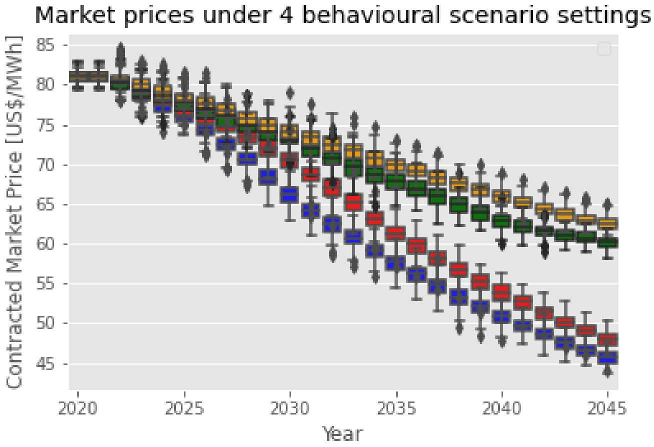

Figure 21: A boxplot of the market price for the duration of the model in four scenarios. Scenario A is blue, scenario B is red, scenario C is green, and scenario D is yellow.

The previous two figures show the influence of price setting and investment behaviour on the contracted market price. In the model, the contracted market price is determined by the average PPA price of the installed capacity. Therefore, changes in the contracted market price occur when the composition of the installed capacity change. This change either happens by decommissioning of old powerplant or construction of new investments. Figure 22 shows the construction of new powerplants for scenarios A and D. Note that the electricity demand increases by 5% each year compared to the previous year. Therefore, the total amount of investments increases each year.

In scenario A '*energy transition'* (top left), gas and wind are constructed in equal numbers for the first two years. After two years, the wind investments increase while gas investments reduce. Solar investments slowly pick up the pace, while coal investments are phased out. Scenario B '*renewable policy'* has the same general dynamic, but thermal energy's investment decline proceeds more slowly. In scenario B, gas investments are the majority investment until 2030, when wind investments pick up. Also, coal investments are part of the investment mix until 2025. Scenario C, '*VRE push by investors',* paint a picture where despite front running investors, the investment in thermal energy remains dominant until 2045. Gas investment and wind increase at a similar pace, but gas has higher total yearly investments. Scenario D '*status quo*' clearly represents the thermal investment dominating during the model horizon. Gas investments increase during the model, and coal investments reduce only slowly. The wind picks up but slower than gas investments. Construction of solar is zero in the beginning and only marginally picks up to one investment per year.

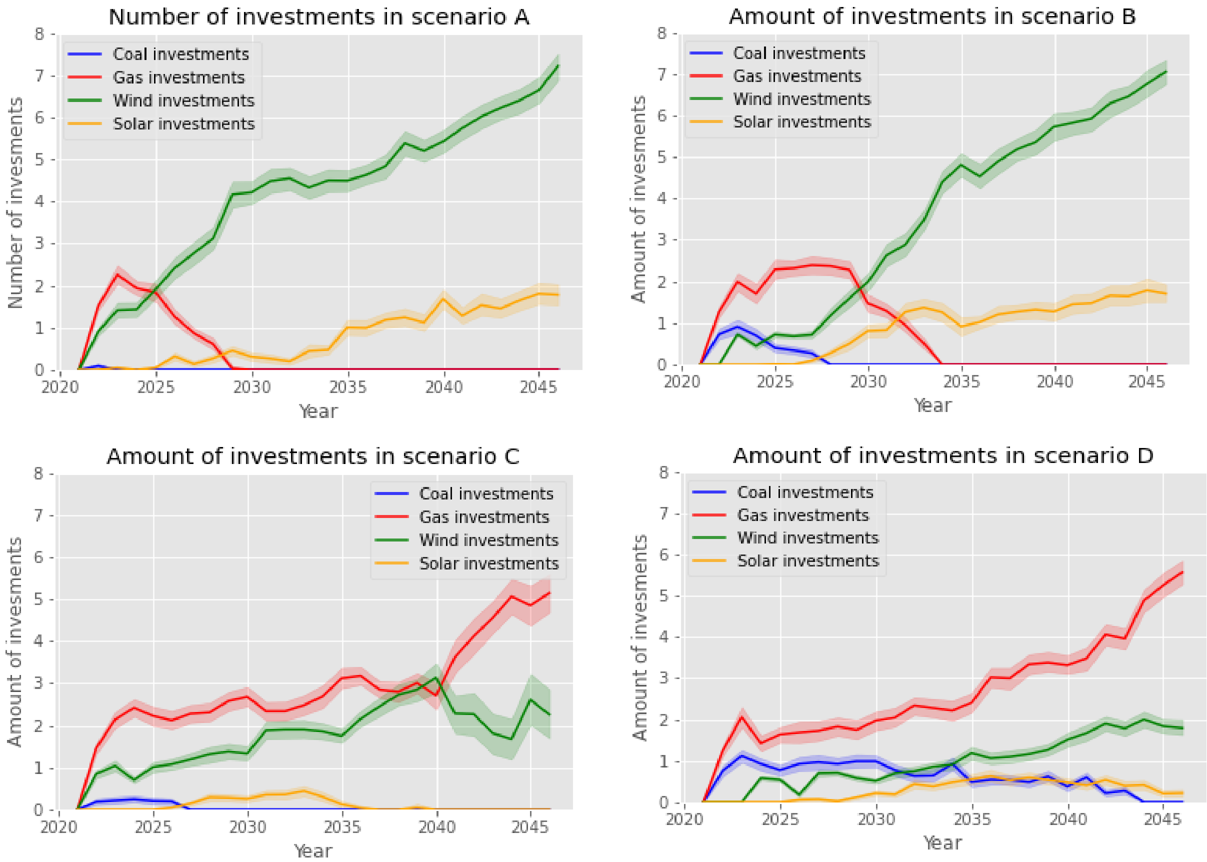

Figure 22: number of investments per year per generation type in scenario A (top left), scenario B (top right), scenario C (bottom left) and scenario D (Bottom right). The lighter colour surrounding the bright line is the 95% uncertainty interval. This means that with 95% certainty, a data point will lay somewhere in the lighter area of each color.

The number of investments depicted in Figure 22 results in an overall picture of the shares of generation alternatives in the electricity mix (see Figure 23). In scenario A, '*energy transition'* (left), the share of renewables rises to around 75%. This is expected given the sharp increase in investments in wind, shown in the previous figure. Scenario B '*status quo*´ lives up to its name with an almost standstill in the share of gas, and a parabolic increase for coal that initially starts and ultimately again ends at a slightly lower level. VRE does pick up but remains a minority share in the total mix.

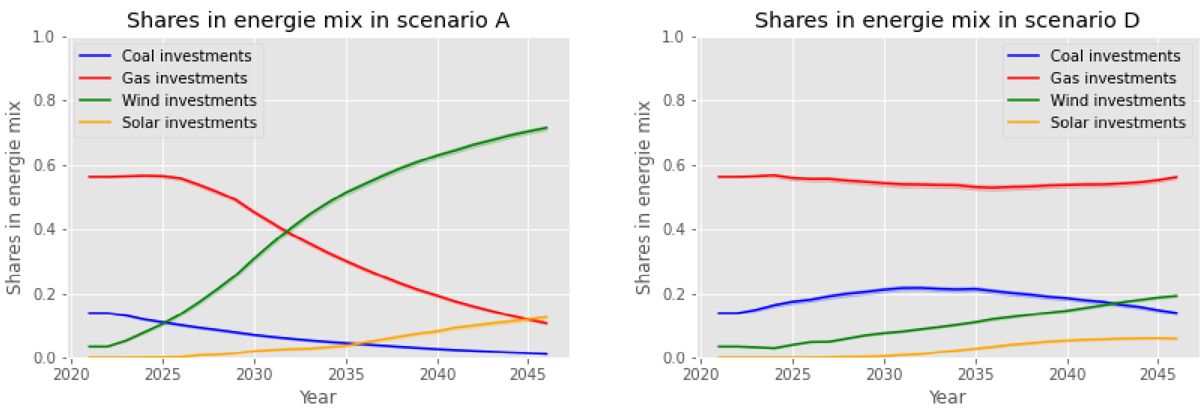

Figure 23: The shares of generation alternative in the total electricity mix for scenario A (left) and scenario D (right)

7.2.3. Conclusion strategies

In all four scenarios, the contracted market price reduces significantly. For scenario A '*energy transition',* the cost reduction is the largest. In scenario A, both investors and the market regulator stimulate the business case of VRE by respectively their view on investment risk and price setting. In this scenario, VRE picks up from 5% in 2020 to a share of ~75% in 2045, and the contracted market price reduces from US$83 to ~US$46. Scenario D '*status quo'* is the other extreme, with both the investors and the market regular unsupportive of VRE integration. In this scenario, VRE picks up to a share of ~25% in 2045, and the contracted market prices reduces to ~US$64.

Scenario B and scenario C lie between the extremes of the other two scenarios. It is observed that the change in price setting by the market regulator has a larger influence on the contracted market price than a change in the investor's behaviour. Refer to Table 1 for all results of the behavioural strategies.

Table 10: the share of VRE in 2045 and the contracted market price in 2045 for all four scenarios.

	Share VRE 2045	Contracted market price 2045 [US$/MWh]	Investors' investment	Market regulator's price-setting
Scenario A 'energy transition'	80%	46	Front runner	Progressive
Scenario B 'renewable policy	70%	48	Follower	Progressive
Scenario C 'push by investors'	35%	60	Front runner	Conservative
Scenario D 'status quo'	25%	64	Follower	Conservative

7.3. Scenarios

The experiments with scenario settings aim to map the influence of the exogenous model variables on the key performance indicators contracted market price, share of electricity produced *by wind/solar/gas/coal.* First, the experiment design is explained, after which the results are presented.

7.3.1. Design of scenarios

The consequence of the complex adaptive socio-technical nature of the electricity system under review is many external variables. Only the high impact/ high uncertainty external variables are captured in a scenario to keep the number of scenarios to a manageable size. The selection is based on the uncertainty and impact on the KPI's of the external variables. Figure 24 presents the results of the classification of the external variables, categorized on high or low levels of impact (vertical axis) and probability of occurrence (on horizontal axis). In the upper right corner, the six external variables are shown, which used in the scenario experiment.

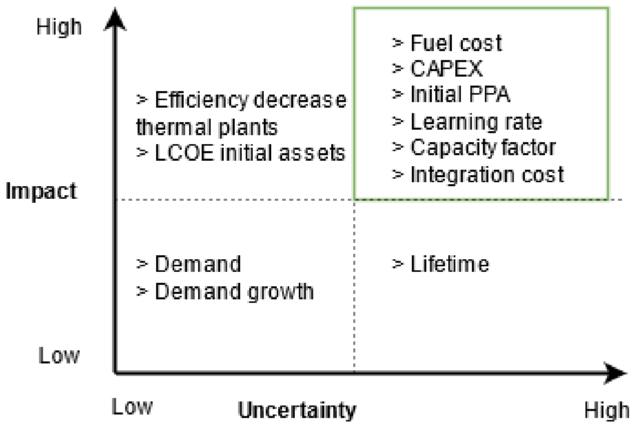

Figure 24: Uncertainty/impact diagram. The upper right top (green square) exogenous model variables have high impact and high uncertainty and are captured in a scenario.

The design of all scenario experiments is shortly explained below:

Scenario 1 (fuel cost): the values range of -50%/+50% is based on the range of fuel prices across different literature sources (please refer to *appendix F for full enclosure).* A fuel price fluctuation of 50% is still modest and mostly covers the initial fuel price uncertainty. The fuel price in the 25 years the model covers, do in reality vary with a factor of 5 when looking at historical data (BP, 2020). The 50% fluctuation is deemed satisfactory to show the influence on the model KPIs.

Scenario 2 (CAPEX): the value range -40%/+40% is based on the comparison of CAPEX data of the National Renewable Energy Laboratory (2020) and PPAs disclosed by NEPRA. The CAPEX for coal differs strongly, i.e., with a factor 3. Gas has only a 10% gap. The CAPEX of Solar and Wind change strongly over time due to the steep learning rate. The comparison of 2020 data between NEPRA and National Renewable Energy Laboratory (2020) shows a factor 2 difference for solar and a 40% difference for wind.

Scenario 3 (initial PPA): the value range -20%/+20% is based on comparing two coal powerplant PPA approvals disclosed by NEPRA. The two projects are China Power Hub 2016, and Lucky electric 2015, and the cost-plus compensation as part of the PPA price determined by NEPRA differs 15%. The difference in PPA prices for the solar project is far larger due to the high learning rate. To strike a balance between the data from the two coal projects and the larger differences between VRE projects, a value of +20% is selected.

Scenario 4 (VRE cost reduction): the value range of 2% (low), 10% (medium), and 18% (high) covers the whole spectrum of VRE cost decrease opted by Our World in Data (2020), National Renewable Energy Laboratory (2020), IRENA (2017). For more information, please refer to Appendix G.2.

Scenario 5 (capacity factor): the value range of -20%/+20% is based on the capacity factor data comparison part found in appendix E. In this part, four sources are compared. For coal, the capacity factors are within the range of 20%, gas within 40%, wind within 60% and solar within 20%. Therefore, a range of +40% is considered appropriate.

Scenario 6 (integration cost): this scenario is based on a switch that does (on) or does not (off) add VRE integration costs to the PPA price of a newly build VRE powerplant. For more information on the levels of integration costs refer to appendix G.1.

7.3.2. Results scenarios

Each scenario is discussed: The key takeaways are presented in bullets at the end.

Scenario 1: Fuel price

Scenario 1 is run independently for the coal price and the gas price, both at three different parameter settings, i.e., -50%/ 0 / +50%. The results are presented in Figure 25 and Figure 26. When fuel prices are high, no investments in coal and gas are made at all. At the default levels, such investments are still made, but the amounts invested are lower. The number of investments for gas (figure 9, right) shows a tipping point in 2027. The business case becomes increasingly negative for the default fuel price (0.25), and investments slowly decline. The low fuel price (0.125) does meanwhile steadily rise.

A point to notice in the contracted market price is that fluctuations in the gas price do change the contracted market price significantly (Figure 26, left), while the contracted market price only slightly differs in the case of coal (Figure 25, right).

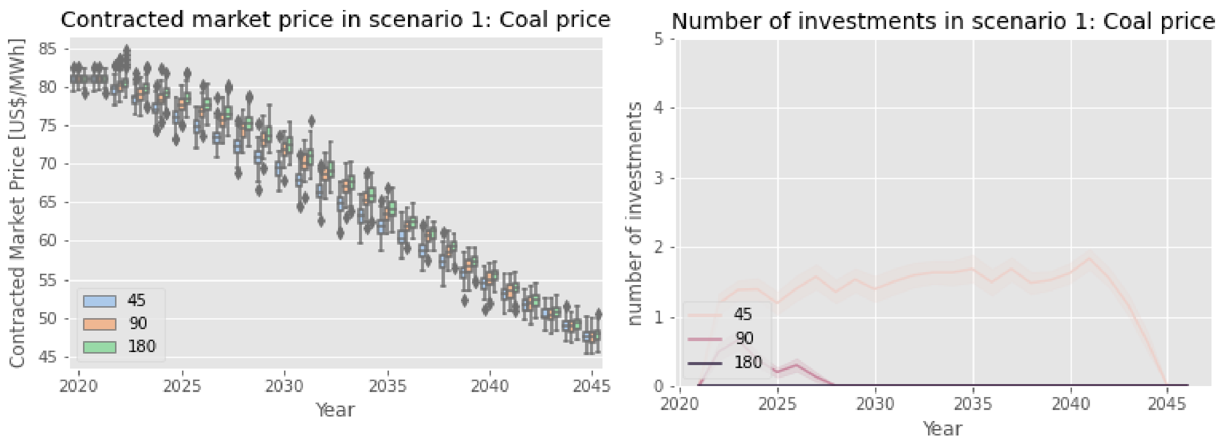

Figure 25: The contracted market price (left) and share of coal (right) when differentiating the coal price

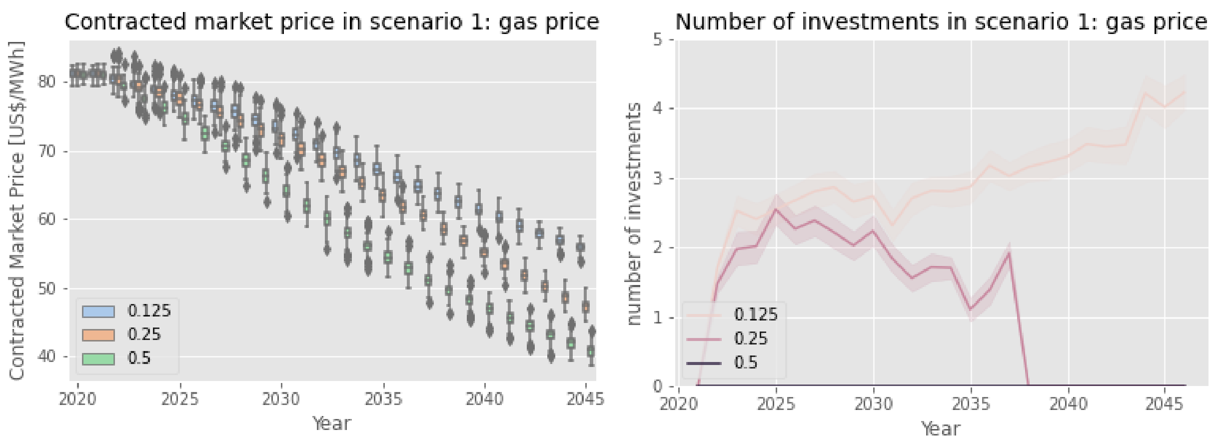

Figure 26: The contracted market price (left) and the share of gas (right) when differentiating the gas price

Key takeaways fuel prices

- If the fuel price increase, fewer investments are made in coal and gas
- No investments are made in coal or gas assets at high fuel prices (+50 compared to default value).
- The contracted market price is sensitive to changes in gas prices, and it is only slightly sensitive to coal prices.

Scenario 2: CAPEX

Scenario 2 is run independently for coal, gas, wind and solar, all of them with 2 or 3 parameter settings (-40%, [0], +40%).

When looking at the share of the generation alternative in the total electricity mix, all four generation alternatives follow the same behaviour. When the initial CAPEX of coal and gas rises, their average share declines, see Figure 27.

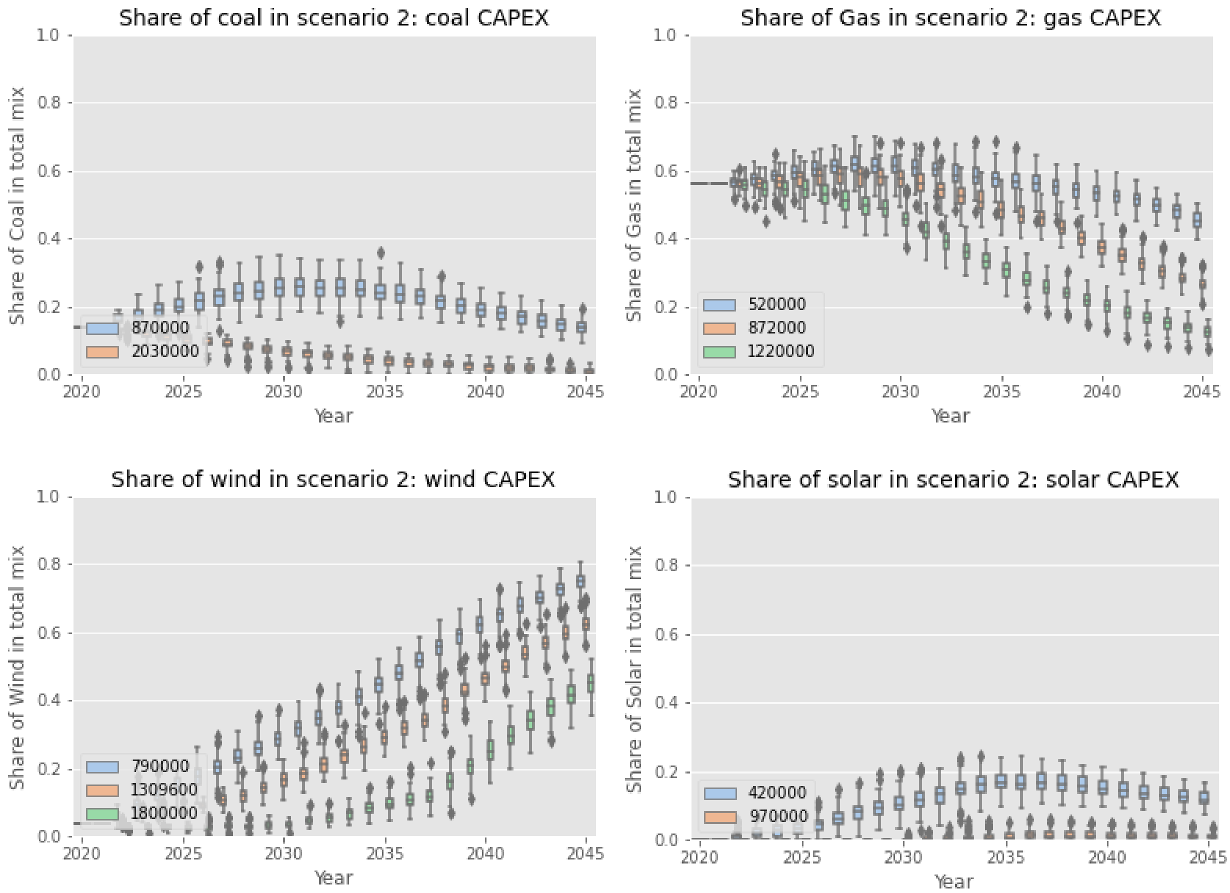

Figure 27: Share coal (top left), gas (top right), wind (bottom left), solar (bottom right) when changing the initial CAPEX of the respective generation alternative.

Figure 28 explains why the contracted market prices remain fairly equal (below) even when the share of wind changes significantly due to higher initial CAPEX. When the share of wind is low at high initial CAPEX (left), the share of solar (right) is high, and vice versa. What happens is that a relatively better business case compensates for the worsening of the business case by the VRE counterpart. This type of behaviour could therefore be marked as the 'compensation by counterpart' effect. The same analysis but then for gas also shows the 'compensation by counterpart' effect with coal.

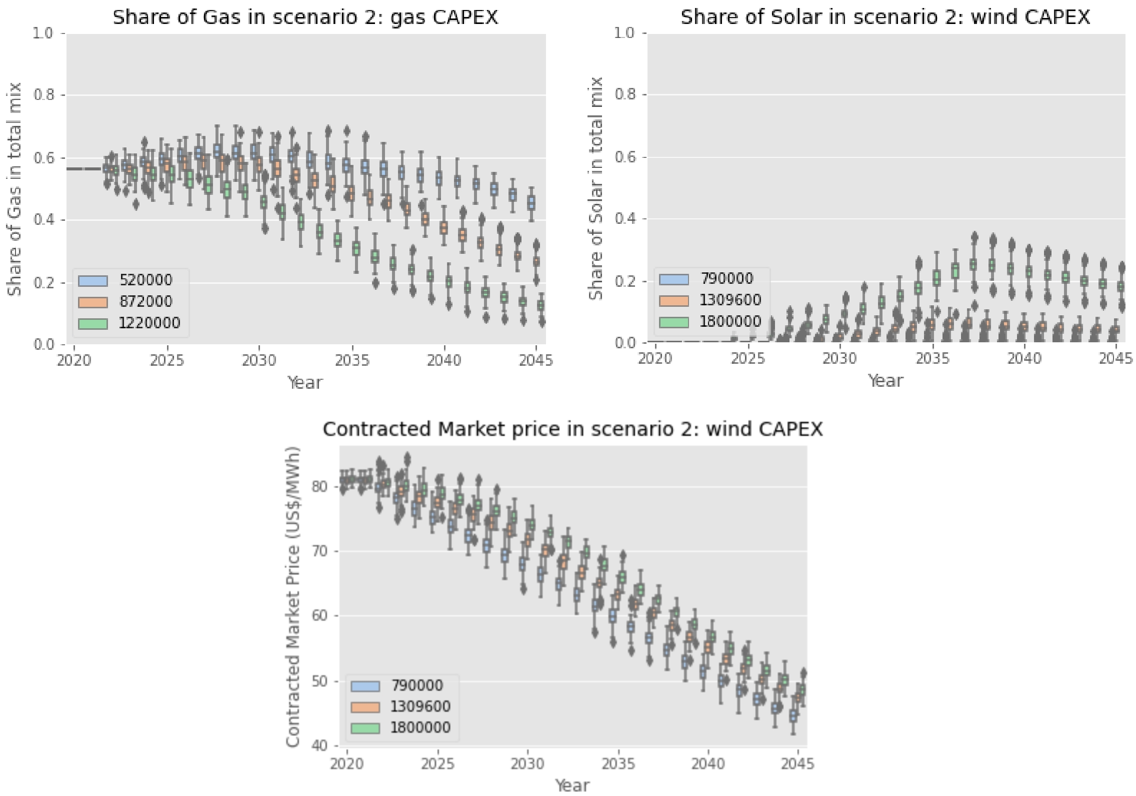

Figure 28: Share of wind (left) and solar (right) in the total electricity mix when changing the initial CAPEX of wind. Below, the contracted market price when changing the initial CAPEX of wind is depicted.

Finally, the number of investments in gas and wind show interesting behaviour. Figure 29 (left) shows an abrupt decline in gas investments depending on the height of the CAPEX value. Figure 29 (right) shows rising wind investment numbers for the two highest CAPEX values that converge to the lowest investment value. In the next chapter, this is analysed.

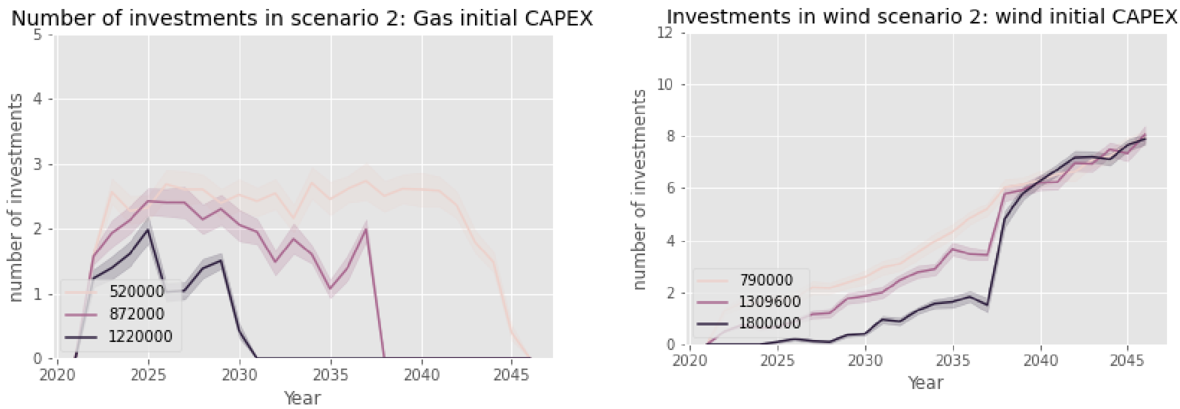

Figure 29: Number of investments in gas (left) for variation in the gas CAPEX. On the right side, the number of investments in wind is depicted for variation in the wind CAPEX. Note that the value of y-axis is different in these graphs.

Key takeaways initial CAPEX

- If the initial CAPEX increases, the respective share in the electricity mix declines. This holds for all four generation alternatives.
- If the initial CAPEX increases for one VRE source and therefore the related investments decline, the VRE counterpart's number of investments do however increase. Therefore, the contracted market price does not differ strongly between initial CAPEX values.
- The '*compensation by counterpart*' effect also holds for thermal sources.
- The number of investments in gas do stop in these scenarios abruptly. When this happens, does depend on the initial CAPEX of gas.
- The number of investments of the two highest CAPEX values in solar converges to the lowest CAPEX value.

Scenario 3: PPA prices

For different PPA prices, a differentiated behaviour is expected to occur. Figure 30 shows that high initial PPA prices result in a higher share in the total electricity mix than low initial PPA prices. This holds for all four generation alternatives. For the two thermal sources (top), the weight in the energy mix is roughly maintained for the high initial PPA. In the low PPA price scenarios, the share steadily declines because few new investments are made, and older powerplants are decommissioned. For VRE at high PPA prices, the share increases significantly compared to low PPA prices. Wind becomes the majority source around 2037 when the PPA prices are 56 US$/MWh.

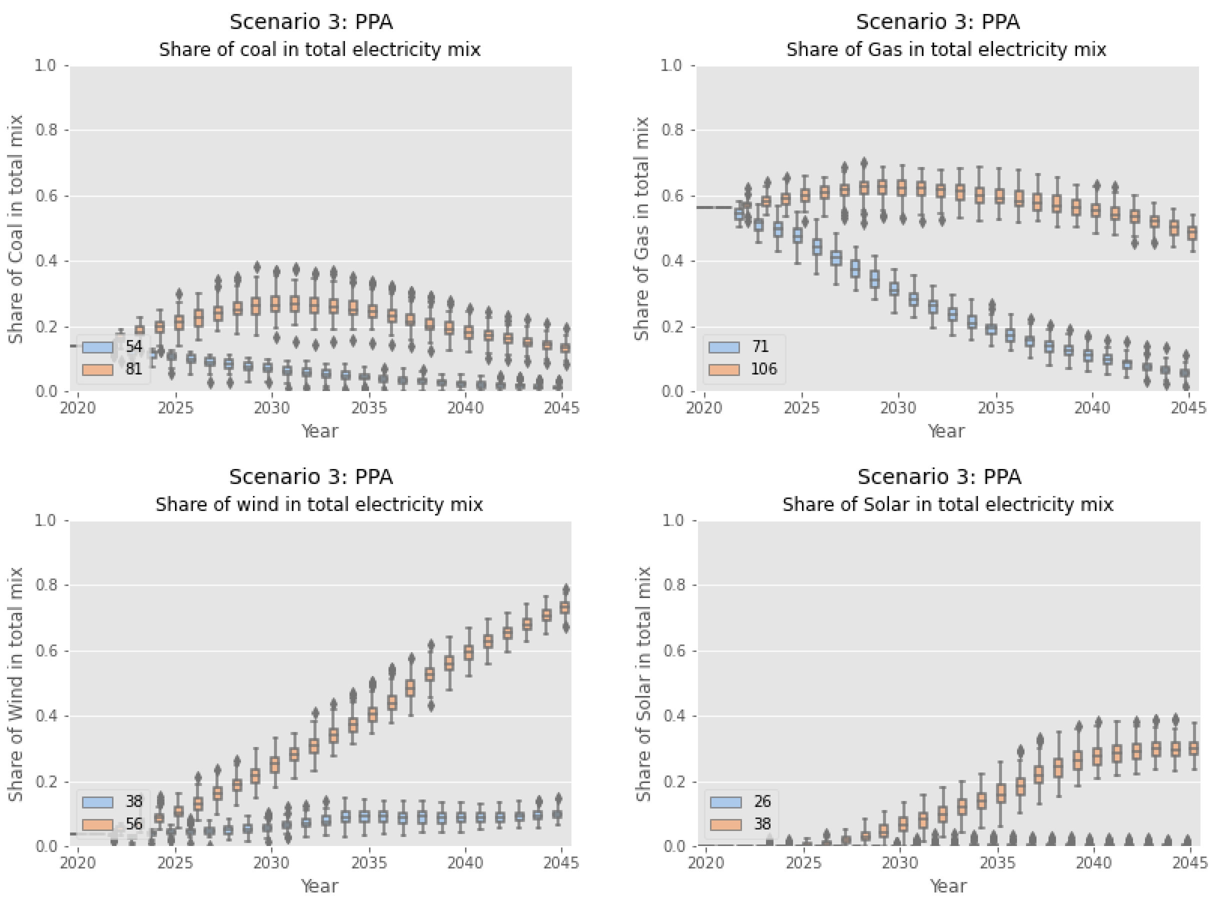

Figure 30: Share coal (top left), gas (top right), wind (bottom left), solar (bottom right) when changing the initial PPA price of the respective generation alternative.

Figure 31 shows that the contracted market price for gas (left) is significantly different for the two PPA values. For solar (right), the contracted market is roughly the same value during the whole model run. This seems odd because with a higher share of solar lower market prices would be expected. However, the share of VRE in the total electricity mix remains roughly the same, see

Figure 20. Because the share of VRE remains roughly the same (see Figure 31 below) and the PPA prices of solar and wind are comparable, the contracted market price remains the same. This is also an example of the ‘compensation by counterpart’ effect.

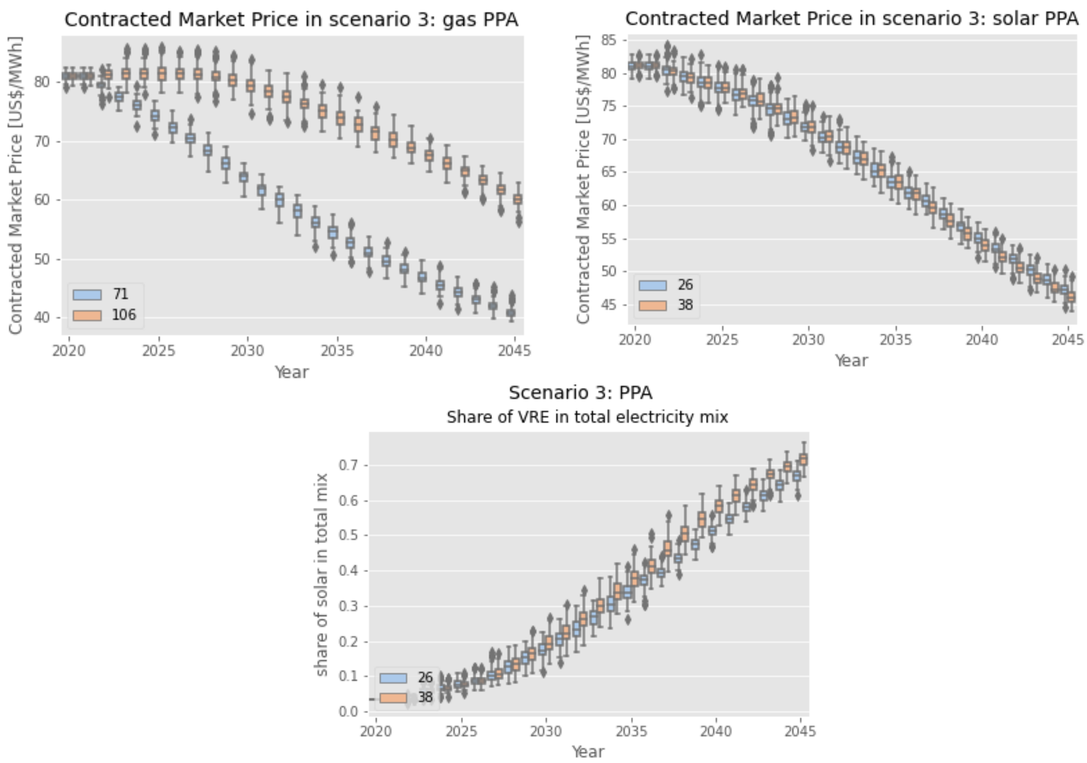

Figure 31: The contracted market price in the gas PPA scenario (left) and in the solar PPA scenario (right). At higher PPA prices, the contracted market price is significantly higher than with lower PPA prices for gas. For solar, the contracted market price remains roughly the same. Below, the total share of VRE is presented for the two different values of initial solar PPAs.

Key takeaways initial PPA prices

- Higher initial PPA prices result in a lower share in the energy mix for all four generation alternatives.
- VRE sources show a steady contracted market price when the initial PPA are differentiated. This is the result of the ‘compensation by counterparts’ effect.
- Gas shows a significant difference in contracted market prices when the initial PPA prices are differentiated.

Scenario 4: VRE cost reduction

Figure 32 shows that a higher cost reduction results in a higher share in the total electricity mix. The exception is the two lowest cost reduction rates for solar (right), in those cases (almost) no investments are made. It seems from Figure 32 that cost reduction rates have a tipping point effect. Especially for wind (left) this can be observed. The highest two cost reduction rates result in relatively high shares of wind while the lowest results in almost no wind investments. The nominal distance between the three cost reduction rates is equal, but between 10% and 2%, the investment decreases much more compared to 18% and 10%. There is a tipping point between 10% and 2% where the business case of solar (below) becomes (much) more competitive than wind and seize most of the investments. In this business case, wind investments remain ow while those in thermal generation continue slightly longer. The compensation effect of investors who jump from one renewable investment to the other keeps the contracted market prices (bottom right) relatively stable even if the investment is low or zero in one renewable energy type. However, the gap of 10

US$/MWh (bottom right) between the lowest (2%) and medium learning rate (10%) remains significant.

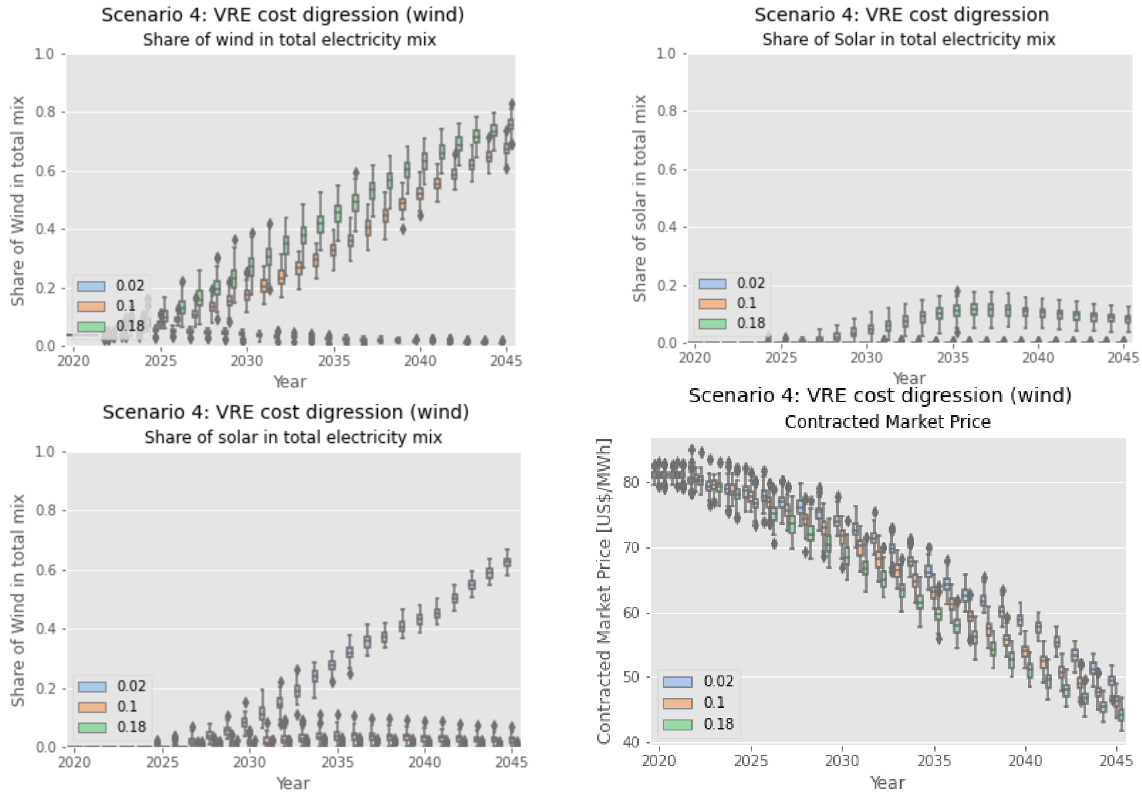

Figure 32: Share of wind (left) and solar (right) in the total energy mix when the learning rate is varied in three ways. The bottom left shows the share of solar in the energy mix when wind is varied. On the bottom right, the contracted market price is depicted when wind is varied.

Key takeaways cost reduction rates

- Higher cost reduction rates result in a higher share in the energy mix.
- There is a tipping point where the business case for solar becomes (much) better, and the investments in wind reduce.
- There is a 'compensation by the counterpart' effect which keeps the contracted market price relatively stable. A significant gap in the contracted market price between the lowest and highest cost reduction rate remains.
- Lower 'cost reduction rates' for wind result in a longer period of investments with thermal powerplants in the equation.

Scenario 5: Capacity factors

Figure 33 shows that a higher capacity factor results in a higher share in the energy mix compared to a lower capacity factor. The differences compared to the previous four experiments are modest, but it should be remembered that this scenario is differentiated -20%/20%, which is the lowest spread of all scenarios.

Figure 33: Share coal (top left), gas (top right), wind (bottom left), solar (bottom right) when changing the capacity factor of the respective generation alternatives.

Key takeaways capacity factor
➢ When the capacity factor increases, the share of the respective generation alternative is higher compared to a lower capacity factor

Scenario 6: Integration costs

Figure 34 shows that if integration costs are included, the market price increase. Integration costs only influence the contracted market price for new VRE assets and does not influence their business case. Therefore, the share of VRE (right) is of equal but minimal impact in both settings.

Integration cost for newly build VRE assets is raised in stages (for more information, refer to Appendix G1). The divergence accelerates around 2034. This goes hand in hand with crossing the 25% VRE mark, which increases the integration costs to the next stage.

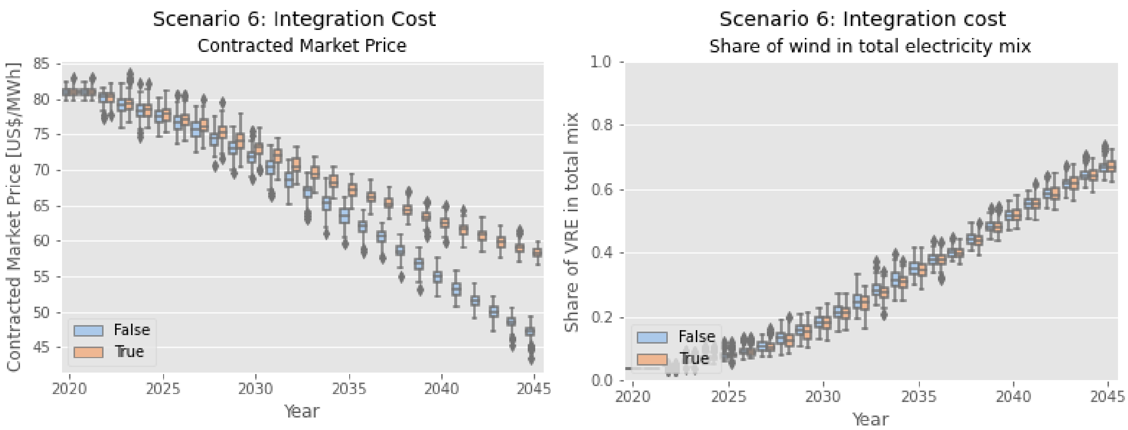

Figure 34: Contracted market price (left) and share of VRE in the total energy mix (right) when integration costs are included and not included.

Key takeaways integration cost
➢ If the integration costs are added to the contracted market price increases, the divergence of the contracted market price accelerates in 2034.

7.3.3. Conclusion scenarios

From the six scenario experiments, it can be concluded that in all scenarios, except integration cost, have a significant impact on the electricity mix. Scenario 6 ‘integration cost’ is left out because the variable integration cost does not influence the business case of generation alternatives.

Furthermore, the ‘compensation by counterpart’ effect is observed multiple times. This means that the contracted market price remains relatively stable while the share of one generation alternative might change substantially but get ‘compensated’ by the other VRE-technology. This is due to compensation by the VRE/Thermal counterpart that increases its number of investments when its counterparts’ investments decrease. Observations from scenario 4 ‘VRE cost reduction’ add that the ‘compensation by counterpart’ effect does not equalize the contracted market price entirely.

8. ANALYSIS

The eight chapter aims to interpret and analyse the effects of the experiments. This is structured in three pillars: (i) core model behaviour fundamental to all results, (ii) analysis of the behavioural scenarios and (iii) analysis of the scenario experiments. The effect of the experiments is measured by the KPI's *contracted market price* and *share of generation alternatives in the energy mix*.

8.1. Core model behaviour

For the analysis of the experimental results, a closer look at the core model behaviour is necessary. The core model behaviour explains why input variables influence the KPI's.

8.1.1. Business case

The output of the agent-based model revolves around the business case calculations by the three types of investors, see Figure 35. The business case calculation, represented by the Net Present Value (NPV), determines the chance an investment is made. The highest NPV has the biggest chance and the lowest, still positive, NPV has the lowest chance to be constructed. All three investors make separate investment decisions each and every year. Collectively this determines the aggregated of the investments done each year. In turn, these yearly investments influence the shares of the generation alternatives in the electricity mix. The average PPA values of the collective assets in the electricity market shape the contracted market price. Two other factors influence the KPI's without being shaped by the business case: decommissioning of old powerplants, because this influence the share of generation alternatives, and integration cost because it influences the contracted market price.

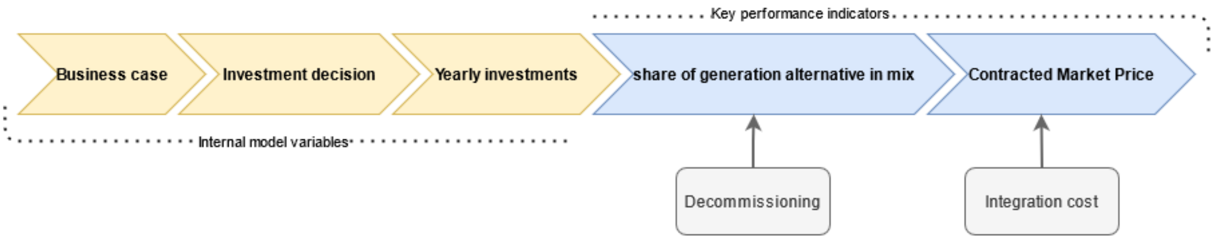

Figure 35: The influence of the business case on the internal model variables (yellow) and KPI's (blue). The business cases, defined by the net present value calculation, shape the investors' yearly investment decisions. The separate investments are brought together in the cumulative yearly investments. This, in turn, shapes the share of generation alternatives in the energy mix. The average PPA values of the collective assets in the electricity market shape the contracted market price. Two factors that operate independently from the business case are the integration cost that increases the contracted market price and decommissioning old powerplants.

The behavioural strategy and all scenario experiments, except scenario 6 integration cost, influence the business case. By influencing the business case calculation, other decisions are made at the arrows in the chain of Figure 35.

8.1.2. PPA and CAPEX decline

The second core model assumption is the fact that PPA prices decline over time. The PPA price is the revenue per produced MWh for an investor. The PPA price is the only source of income for an investor. Therefore, if the PPA price declines and the cost side of the business case remains equal the NPV declines. For thermal generation alternatives, the cost side of the business case remains equal over time. For VRE, the CAPEX (initial investment costs) decreases with the reduction rate of VRE. For thermal generation alternatives, this means that over time a negative business case is inevitable. The settings of the external and behavioural variables determine how long it takes before the business case of thermal becomes negative, and VRE becomes competitive.

Think of it as two cars on the highway, with the thermal car in front but standing still or moving in 1st gear and the VRE car racing at full speed. The external and behavioural variables influenced the number of kilometres the thermal car is in front and the speed with which the VRE car drives.

In sum, there is always a movement towards increasing VRE in the model because the PPA prices always decline, and only the CAPEX of VRE sources decline.

8.2. Analysis of the behavioural experiment

The behavioural strategy of the market regulator and the investors encompass two variables, the PPA price and the discount value. Both variables do influence the business case of generation alternatives.

The results show a significant impact when both the discount values and the PPA prices are changed. However, the influence of the PPA price setting by the government is far larger than that of the investors' attitude. In the two scenarios (C & D) with a conservative market regulator, thermal energy stays the dominant investment until 2045, even when front running investors follow through on VRE investments and accept higher risks. Nevertheless, the difference between a positive and negative view by investors is significant. When VRE investors are positive, VRE becomes a serious alternative for thermal energy with 40% in the energy mix, while a negative view keeps VRE at 25%.

When the tables turn and the government act progressively towards VRE and reduce the PPA prices, VRE investments take off from the first instance and take over from thermal between 3 to 10 years. This pushes the share of VRE up and brings the contracted market price down faster than the other two scenarios.

When interpreting these results, it should be remembered that the behaviour of the market regulator is simplified and would in the real world be unpredictable. In chapter 5, the parameter setting for the market regulators is determined and explained. Therefore, the uncertainty around the decline of the PPA-prices is still large. It will most likely not behave uniformly over all generation alternatives and decline with a fixed annual reduction. With these reservations in mind, the results should be interpreted as possible futures that give a feeling for how the future could unfold.

Key takeaways behavioural experiment

- The market regulator's influence on the modelled electricity system of Pakistan is more dominant than the influence of investors.
- The consequence of a conservative market regulator is that thermal energy stays the dominant player in the market.
- When investors skew towards a positive view on VRE, they can collectively lift renewable energy from a minority source (25%) to a serious alternative (40%).
- A progressive market regulator results in a fast-paced renewable energy transition.
- Based upon this study, it looks that the behaviour of the market regulator is crucial and most impactful under all scenarios.

8.3. Analysis of the scenario experiments

The most apparent observation from the scenario experiments is their high impact on the model KPI's. The high impact manifests in large fluctuations in the shares of generation types in the fuel mix. Especially *fuel cost*, *initial PPA,* and *VRE cost* have a very high impact on the model KPI's. They also have very uncertain as described in section 7.2. 'Design of scenarios. This is visually represented in Figure 36 with the addition of the other scenario variables.

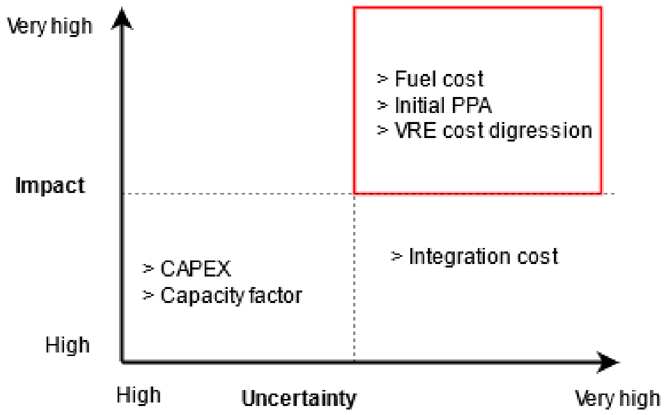

Figure 36: Impact versus uncertainty matrix to sort the external variables into high/very high uncertainty and high/very high impact. The very high impact and very high uncertainty are further analysed.

This uncertainty quadrant, as shown above, asks for explicit attention when designing policies or planning for investments.

A dampening effect in the fluctuation of the contracted market price is the ‘compensation by counterpart’ effect. This effect is observed at scenario 2: *initial CAPEX*, scenario 3: *PPA prices,* scenario 4: *cost reduction rates*. The ‘compensation by counterpart’ effect keeps the contracted market price steady under different parameter settings while the generation type share swings strongly. The steady contracted market price is the result of an increase in investment by one of the thermal/VRE counterparts when investments fall in the other.

The reason for the ‘compensation by counterpart’ is rooted in the NPV calculation for the business cases. In the start phase of the model, the NPV of VRE is negative while thermal is positive and vice versa for the last phase of the model. For investors, there is no difference because they have no other choice than thermal in the starting phase and VRE in the end phase. The only difference occurs in the short middle section, where thermal and VRE business cases are similar. When gas is downplayed, the transition to VRE is a bit quicker, or when wind is downplayed, investment in gas continues for a few years more. This middle section is short and therefore of limited influence on the contracted market price.

The ‘compensation by counterpart’ effect learns that it is important to encourage VRE and discourage thermal along with the whole range of investment opportunities when a quick transition is desired. Furthermore, it should be emphasised that the dynamics that discourage VRE altogether reduce the renewable transition more than a dynamic focussed on a particular VRE type.

Furthermore, tipping points are observed in scenario 1 *fuel price* and scenario for gas investments, in scenario 3 *initial PPA prices* for wind investments, and scenario 4 *VRE cost reduction.* At the default value (0.25 US$/m^3), the number of investments in gas units is between 1-2 each year until 2038. When the fuel price is doubled, there are no investments in gas units. When the value is divided by two the number of investments increases each year. For wind investments in scenario 3, only a 20% decline in initial PPA prices results in a 10% share of wind instead of a 60% share in 2045. The cost reduction scenario for wind shows that a 10% yearly cost reduction results in 70% wind in 2045. A 2% cost reduction results in 0% wind in 2045. The same eight percent difference but then between 10% and 18% only increases the wind share by 5-10%. These tipping points are valuable to consider when designing new policies or considering investments.

Key takeaways scenario experiments

- The analysis of the scenario experiments reveals a large uncertainty space.
- The ‘compensation by counterpart’ effect encourages a broad approach where multiple renewable energy sources are stimulated. With such an approach, the chance that at least one type of VRE prevails increases.
- The ‘compensation by counterpart’ effect emphasises the importance of sharpening dynamics that discourage VRE integration altogether.
- There are tipping points where investments in a generation alternative are stable. An increase/decrease let the investment diverge to high numbers of investments or (almost) none.

8.4. Conclusion

This chapter aims to answer the question of the effect of different investment and price-settings strategies on the future market price and energy mix of Pakistan. From the results in chapter 7 and the analysis of chapter 8, it can be concluded that different investment attitudes by investors and price-setting strategies by a market regulator are significant. The effect of the market regulator's price-setting strategy is larger than the investments strategies of investors. Despite the uncertainty in the market regulators future price-setting strategy, it can be confirmed that the market regulator is able to steer the future energy mix and by doing this, steer the contracted market price. On the other hand, investors can adjust the direction of the energy transition but are bound to the strategy of the government.

Another conclusion is that the impact of the investment and prices setting strategies take around 5-years to take effect. In the first 5-years of the results, the market prices are almost identical. Only after that period, a diverged pattern emerges. Put differently, the market regulator needs to determine a 5-years of steady policies to see the desired impact of their policy intervention.

The scenario experiments show that the model is highly sensitive to variations in the external variables. This sensitivity is expressed in the market shares of the different generation types. It is expressed less in the contracted market price. This is due to the ‘compensation by counterpart’ effect in which a decline in investments by one VRE/thermal source is compensated by its thermal/VRE counterpart. This effect makes the contracted market price robust for to shocks focused on one generation type.

In line with the sensitivity of the model are the notions of tipping points. These are points where a slight change in a scenario value results in a large change in the number of investments in a generation alternative. Tipping points are observed in the scenarios on fuel prices, VRE cost reduction, and initial PPA values. These points are important to bear in mind when policies are designed.

9. VALIDATION

9.1. Results validation by literature comparison

Validation of the decline of contracted market price in all scenarios

The government is under huge pressure from the media to reduce generation costs, further enlarged by the circular debt crisis. Therefore, NEPRA only accepts PPA prices that bring savings to the government (personal communication, June 17 2021, Appendix C.5). This dynamic only increases with the current overcapacity of electricity production. The only exception on this is coal power plants because of the intended domestic coal production of coal. Therefore, the model result that the contracted market price declines in all scenarios are realistic.

Validation of a stronger decline of the contracted market price with high shares of VRE

Furthermore, VRE has lower generation cost than thermal production. Therefore they have lower PPA prices, and thus the contracted market price is lower (personal communication, June 17 2021, Appendix C.5; personal communication, April 14 2021, Appendix C.2; Zameer and Wang, 2018). The difference in PPA prices between VRE and thermal can be checked by looking at the publicly available PPA tariff decision of NEPRA (NEPRA, 2021). Therefore, it is realistic that the scenarios with higher VRE shares have lower contracted market prices.

9.2. Validation by model comparison

The second method for validation is model comparison. The Pakistan optimisation model developed by The World Bank (2020b) and the agent-based investment model by Kraan et al. (2018) are used. Both models have validated themselves. Therefore, the comparison increases the usefulness of the agent-based model to explain possible futures and behaviour dynamics (van Dam et al., 2013). The comparison aims to explore whether the range of the agent-based model results makes sense when compared to other models. Large deviations are explored further, and implications for model interpretation are stated.

9.2.1. Model comparison with optimisation model of The World Bank (2020b)

The optimisation model concerns a model of the Pakistan electricity market between 2020 and 2040. The results are presented in 18 scenarios. The optimisation model's primary goal is to research the optimal pathway to a desired combination of greenhouse emissions and system costs.

Hydro power not included. First, a distinct difference between both models is that the World bank model includes a wider range of sources than the agent-based model. The influence of hydropower is especially influential in the World Bank model ranging from 25% - 40% in 2040.

Validation of the VRE shares. The range of VRE penetration over the different scenarios is between 50% and 30% in the World Bank model. The ratio of solar PV to wind within the VRE penetration is between 75% solar/25% wind and 66% solar/33% wind. The figure presented in chapter 7 (Figure 20), show have a VRE penetration rate in 2040 between 20% and 80%. The ratio of solar to wind is 17% solar / 83% wind and 33% solar / 66% wind. The VRE penetration rates in the agent-based model are wider than the ones calculated by the World Bank. The observation remains true even when the exclusion of hydro is considered. Therefore, it can be concluded that the agent-based model is more sensitive compared to the World Bank model. To put this directly in perspective: the European electricity system agent-based model of Kraan et al. (2018) shows even larger ranges of VRE penetration in the model. This does also point to a difference in type of modelling and related assumptions.

Furthermore, the difference in VRE ratios between both models is like a mirror. This is the result of a different perspective on the potential of solar PV for Pakistan. The World Bank did an in-depth study of wind and solar potential in Pakistan for different parts of the country. From this, the conclusion was drawn that the potential of solar PV is very large due to favourable conditions, the potential locations with high wind speeds is scarce. The agent-based model took the financial data of wind and solar projects built during in the last four years as the starting point. The recently finalized wind farms have sites with high wind spots to their disposal and received relatively favourable PPA prices from the market regulator. Solar PV, while high yield spots are abundant, received rock-bottom PPA prices. This made that wind became more competitive than solar in the model, and thus, the investment in wind is higher than solar. The geographic limitation to the expansion of wind is not considered in the model. Therefore, interpretation of the results should be restricted to VRE in general, and the shares of wind and solar should be seen as indicative to explore the investment dynamic.

Fuel price differentiation. In scenario 8, the base model is run with a 25% and 50% lower cost of gas. The conclusion on this scenario is that (i) a reduction of gas prices results in VRE shares increasing at a lower path compared to the base case, (ii) VRE remain economically viable, and (iii) VRE share in the long term (2040) are just slightly lower compared to the base case scenario. The Pakistan agent-based model dynamic show the same behaviour as observed in the World Bank (2020b) optimisation model. The third conclusion that the VRE share in the long term is only slightly lower is distinctively different. The agent-based models VRE share does not converge to the default gas price VRE trajectory.

Contracted market price. The optimisation model of the World Bank does not provide yearly generation costs for the different scenarios. It does provide the average supply cost (in US$/MWh) for the study period (The World Bank 2020b, 195). This shows only small differences of up to US$10/MWh. The World Bank model is an optimisation model and therefore does search for optimal pathways which clearly provide different dynamics compared to an ABM complex adaptive system approach.

9.2.2. Model comparison with an ABM of the European electricity market by Kraan et al. (2018)

The European investment agent-based model is a generic view on the energy transition of a liberalized electricity market. The aim of the model is the expose emergent behaviour that is expected from an evolving liberalized market during the energy transition.

Large uncertainty space. Kraan et al. (2018) conclude that heterogeneity of decision-making results in a broad probability distribution of outcomes based on the model outcome. This conclusion is in line with the ABM Pakistan model results.

Validation of VRE learning curve. The European ABM uses a cost reduction curve for VRE based on the installed capacity, including a stabilisation level. This approach is more realistic because a learning curve for a new technologies is more evident that for the more-matured technologies (e.g., thermal). When this approach is used in the Pakistan ABM, the PPA price decline should be tuned to this cost curve. The model dynamic would stay roughly the same, with VRE becoming more competitive over time while thermal investments business cases decline.

Key takeaways validation
➢ The ABM of Pakistan's electricity system does not include hydropower, while this is expected to be a major source in the future electricity mix (The World Bank, 2020b).

- The range of VRE penetrations by the ABM of Pakistan's electricity market is higher compared to The World Bank optimisation model. However, the uncertainty margin of Pakistan's ABM is lower compared to the European investment model of Kraan et al. (2018).
- The ABM of Pakistan does not consider the geographical limitation of high yield wind spots and the abundance of solar irradiation. It might, therefore, overestimates the wind penetration and underestimate solar penetration. Shares of wind and solar are counterparts in the ABM and should be interpreted as indicative of exploring the investment dynamic
- When the gas price becomes cheaper, Pakistan's ABM shows the same VRE decline dynamic as The World Bank model. However, in the ABM, the initial fuel prices determine to a larger extent the long term VRE penetration.
- The assumed learning curve approach of the ABM, based upon historic data, is quite helpful but in the future these observed trends might differ or level off: if this happens, this might evoke different investment behaviour.

10. DISCUSSION

The aim of this study is to research the effect of the behaviour of investors and a market regulator on circular debt in the context of the energy transition. The agent-based investment model takes the first step to fulfil the aim of the research by linking behaviour to the contracted market price. The second step is to link the contracted market price to the development of circular debt. This section discusses both steps. First, step one is discussed in section 10.1 by reflection on the agent-based investment model results. Secondly, step two is discussed in section 10.2 by reflecting on the link between the model results on contracted market price and circular debt.

The remainder of the chapter is used to: reflect on the applied ABM approach in section 10.3, and to discuss the limitations of the study regarding actor conceptualisation, the use of assumptions in the conceptualisation of the ABM, and the validity of the data sources in section 10.4.

10.1 Discussion on model results

The main results from the agent-based investment model based on Pakistan's electricity sector are discussed: (1) the market regulator's price-setting strategy has a more significant influence on the electricity price than investors' investment attitude, (2) the endpoint of the model (KPI values in 2045) is largely determined by the model setup at initialisation, (3) the agent-based investment is highly sensitive to variations in the external variables leading to a large uncertainty space and, (4) there are tipping points in the scenario experiments.

First, the market regulator's price-setting strategy influences the electricity price more significantly than the investors' investment attitudes. This result is in line with the theory on single-buyer electricity markets that those markets are sensitive to governmental interference (Course reader, SEN1522 Electricity and Gas, CoSEM master, TU Delft, 2019). In Pakistan, the governmental influence is via the market regulator NEPRA.

The investment strategy of investors is less influential on the model outcomes than the market regulator. However, the development finance institutions' role as early adopters of technology was apparent in all scenarios. This role of DFIs is in line with observations in the energy transition of India, where investments in VRE, financed by Development Finance Institutions (DFI), were dominant in the beginning and shifted to less profitable VRE types later in the transition (Renewable energy to responsible energy, 2021). The reinforcing effect that successful VRE projects increase VRE investments is observed in multiple countries and confirmed for Pakistan with expert interviews. This reinforcing effect is outside of the scope of the model.

Second, the endpoint of the model (KPI values in 2045) is largely determined by the model setup at initialisation. In reality, the starting values are not that rigid but will fluctuate under changes in political viewpoints and external variables (e.g., fuel prices and geopolitical pressure). However, the notion that an initially chosen path is likely to be followed for a longer period aligns with the expectation of path dependence in complex systems such as the electricity sector (Chappin et al., 2017).

Third, the agent-based investment results are highly sensitive to variations in the external variables, leading to a large uncertainty space. The agent-based investment model spans 25-years of the electricity system of Pakistan in transition. During this period, the transition will be influenced by highly uncertain factors such as climate change, geo-political pressure, technological advancement, and socio-economic development (Maier et al., 2016). These factors are influential and highly uncertain and give rise to multiple distinct future states of the electricity system (Maier et al., 2016). The large uncertainty space of the model results is, therefore, congruent with this uncertainty. Furthermore, given the uncertainty of the exogenous variables the model results should be viewed as possible futures that give a feeling for how the future could unfold.

Finally, tipping points observed in three out of six scenario experiments show how small changes can lead to large differences in model outcome. These tipping points are related to external variables that significantly influence the business case of generation alternatives. Investors in the agent-based investment model asses the feasibility of an investment using a Net Present Value (NPV) calculation. The resulting NPV value can be negative or positive. If the value is positive the generation alternative could be built, and if the value is negative, no investment will be made. A tipping point value pushes the business case hovering around a zero value, above or below the threshold value of zero for a possible investment. The notion of tipping points is also used in studies that research the maximum price for new technology to be competitive with the incumbent technologies (Cesaro et al., 2021). A remark is that tipping points also refer to a point where a particular trend becomes self-reinforcing, like climate change (Bernard et al., 2021). The linear nature of the agent-based investment model does not account for this effect.

10.2 Discussion on the link between the model results and circular debt

In section 2.3 of the literature review, it is stated that there is a positive causal relationship between the contracted market price and circular debt in Pakistan. According to Zameer et al. (2018) and Mahmood et al. (2014), a decline in the contracted market price will reduce circular debt. By conducting expert interviews and observing Pakistan's historical circular debt crises, this study extends the already existing rationale by presenting a qualitative analysis.

According to Zameer et al. (2018) and Mahmood et al. (2014), the positive correlation between lower contracted market prices and a reduced circular debt appears very solid. This study found, however, that the causal link is not as direct as it may look. The subsidy savings due to lower contracted market price can be redistributed in many ways. It can reduce circular debt by increasing the subsidy payment to DISCOs, lower end-user tariff, or reduce the sovereign debt position. These options are best explained using the two equations presented in chapter 3.

$$(1) \qquad TDS = CRT - end\ user\ tariff$$

$$(2) \qquad Debt\ DisCo = Unpaid\ TDS + above\ CRT\ costs$$

First, a recap of the formulas and definitions is provided, then, one by one, the ways to redistribute savings are discussed.

Eq. (1) defines the Tariff Differential Subsidy (TDS) as the difference between the Cost Recovery Tariff (CRT) determined by NEPRA and the end-user tariff (what consumer pay) determined by the Ministry of Energy. The CRT is the electricity tariff that NEPRA assumes a Distribution Company (DISCO) needs to earn per kWh to cover all its costs. If the end-user tariff (electricity tariff for consumers) is lower than the CRT, the Government of Pakistan (GoP) fills the revenue gap with the Tariff Differential Subsidy (TDS). The Cost Recovery Tariff (CRT) considers (I) the contracted market price of electricity, (II) reasonable assessed T&D losses, (III) 100 percent bill collection (Bacon 2019, 34). Changes in the contracted market prices influence the Cost Recovery Tariff (CRT) set by the Pakistani market regulator NEPRA shown in Equation 1. According to NEPRA's formula, the CRT for DISCOs should increase when the contracted market price increases and vice versa.

Eq. (2) shows two sources of debt accumulation: unpaid TDS and above CRT costs. The unpaid TDS is the result of the inability of the government of Pakistan to pay the full subsidy to the DISCO's, due to the precarious financial situation. The 'above CRT cost' results from a mismatch between NEPRA's cost recovery tariff and the actual revenues necessary to cover all costs. The actual tariff needed to cover all costs is called the full-cost recovery tariff. As mentioned before, NEPRA considers three main elements for the calculation of the cost recovery tariff: (1) the contracted market price of electricity, (2) transmission cost with limited electricity losses, and (3) 100% bill recovery (i.e., all end-user paying their electricity bill to the distribution company). However, in reality, distribution companies have lower bill recovery levels (i.e., not all end-users pay their electricity bills) and higher electricity transmission losses. The costs that are higher than prescribed in NEPRA's cost recovery tariff are unsubsidised, increasing distribution companies' debt.

The first way to redistribute savings of a lower contracted market price is by using the decline of NEPRA's cost recovery tariff to increase the subsidy payments to DISCOs. According to eq. (1) a decline in CRT results in a decline of the TDS. A lower TDS means less pressure on the government budget for TDS payments to DISCOs. Therefore, it is more likely that the government pays the TDS in full and on time to the DISCOs. If this happens, DISCO's will stop accumulating more debt, and therefore circular debt stops accumulating.

Secondly, a decline of the CRT can also be used to lower the end-user tariff to increase popularity among the citizens. In this case, the TDS remains equal, and most likely, the default on TDS payment remains equal, resulting in more debt accumulation at DISCOs.

The third way to redistribute savings is to reduce the sovereign debt position of the government. In this case, the lower contracted market price reduces the CRT. According to eq. (1), a lower CRT means that the TDS amounts reduce. The government could use the reduction of TDS not to pay more TDS to the DISCOs but to reduce the deficit on the account balance of the government. This is not an unlikely scenario because the size of the government deficit is an important metric for risk assessment by foreign investors (The World Bank 2020a, 9). Higher risk assessment increases the interest rates on loans and government bonds.

In sum, there is a positive correlation between production cost and circular debt, but the exact cause-effect is unclear as it is subject to a complex socio-technical decision-making process. The correlation is evident with large shifts in electricity costs as happened during the 1998 crisis when fuel prices skyrocketed (Bacon et al. 2019, 16). However, it is unlikely that small reductions in production costs are directly translated into a decline of the circular debt position. This is due to the sticky political decision-making process with time-consuming procedures and many involved political entities.

10.3 Reflection on the used approach

Chapter 1, section 1.4.4, discusses the application of an agent-based modelling approach to answer the main research question. In that section, key features of agent-based models are highlighted and linked to the research question. In this section, a reflection is presented on the application of the key features in the Pakistani agent-based investment model.

First, agent-based models have key features that allow the modelling of complex adaptive systems: (1) sustain many actors with a heterogenic view on the future, (2) allow for different decision-making thresholds among the same agents, and (3) permit interaction among actors, reshaping their internal states. These key features could be used to model a system consists of many investors who all have their own interactions, decision-making thresholds, and view on the future. With four actors the plurality of investors' view on the future, decision-making thresholds, and interactions is not fully exploited. The decision to model three investors is based on the increased tractability of investments by the investors. Also, three types of investors make the model interaction more comprehensible.

Secondly, the developed agent-based investment model uses a large number of rules and parameters to operate. A rich set of reliable information is, therefore, essential. As discussed in section 10.3.3, the reliability of the input data is predominantly based on grey literature. This type of literature reduces the model's validity. To prevent the usage of biased input data from grey literature, all information is benchmarked with other sources whenever possible. Sequentially, this challenge of reliable input data would also be present for other research methods. Furthermore, many assumptions make the validation challenging, especially with a model that spans multiple decades and covers the electricity system of an entire country.

Thirdly, the feature of agent-based models to deal with imperfect foresight is not explicitly incorporated in the investors' or market regulator's decision-making of the Pakistani agent-based investment model. During model conceptualisation, the trade-off was made between increasing assumptions to allow incorporation of imperfect foresight or a more simplistic and therefore transparent model. The inclusion of imperfect foresight demands an extension of the actor conceptualisation, which includes more assumption.

After this reflection, it is tempting to conclude that the agent-based model could have been more elaborate to capture the complex adaptive nature of the electricity system. One could argue that this increases the persuasion of the model to expose possible transition pathways. On the other hand, (1) the extreme uncertainty already presents in the current model, (2) the challenges to validate the model, and (3) a large number of assumptions are arguments that favour the simplistic nature of the current model.

Finally, when comparing seven types of energy modelling techniques categorised by Subramanian et al. (2018), the choice for agent-based modelling is deemed most applicable to answer the research question. The agent-based modelling approach contributes to a research field with extensive qualitative studies to circular debt and a convincing optimisation model by The World Bank (2020). The central focus of behaviour leaves explicit room for incorporation and analysis of bounded rational decision-making that is a key driver of the circular debt crisis.

To conclude, the ABM approach for the Pakistani electricity system is about striking the right balance between the key features of an ABM and the fundamental challenges in ABM studies: transparency, tractability, and reproducibility (Kraan et al., 2018). The overall view is that despite not exploiting the full potential of the key characteristics of ABM it is an appropriate and valuable application.

10.4. Limitations of the study

10.4.1. Conceptualising actor behaviour

Any agent-based model tries to capture real life behaviour in decision rules and states. For the investment model of Pakistan, two actors were conceptualised: investors and a market regulator.

The investors' risk assessment is based on a single metric and is, therefore, approached too narrow compared to the richness of real-world decision-making. In Pakistan, investors decide on a mix of gut feelings, financial models, macro industrial risks and opportunities, and the potential for follow-up investments (personal communication, June 17 2021, Appendix C.5). Also, there is a considerable upfront investment before NEPRA provide power purchase agreement details that allow for a more pragmatic investment decision. However, the simplistic approach is deemed appropriate for this research as it keeps the model dynamic tractable and transparent.

The Pakistani market regulator NEPRA steers investment in the model by changing the yearly rate with which the production price per MWh declines for thermal or VRE generation. The production price that a generation alternative receives per MWh during its lifetime is agreed in the Power Purchase Agreement (PPA), therefore it is called the PPA price. By altering this metric, the market regulator influences the business case of generation alternatives. PPA prices provided to investors in Pakistan are on a cost-plus basis where the market regulator allows a maximum expenditure for each cost component plus a return-on-investment (ROI). All this financial input is synthesised to a PPA price per MWh, allowing the investor to earn the agreed cost and ROI. By using the approach of a PPA price, the fundamental behaviour of the market regulator determining the profit side of the investment is modelled. In reality, additional provisions co-determine the attractiveness of the PPA contract, but they are of less importance compared to the PPA price metric (personal communication, April 14 2021, Appendix C.2). Therefore, using PPA price decline seems an appropriate metric to conceptualise a market regulator's influence on investments.

10.4.2 Assumptions

This section discusses the most important assumptions which are expected to affect the model outcomes. The full set of assumptions is listed in appendix D.

Exclusion of capacity payments. Capacity payments are contractually agreed obligations of the Central Power Purchase Authority with producers to pay a fee for idle capacity. Excluding capacity payment results in (i) distortion of the contracted market price of electricity and (ii) an incorrect optimistic view of the attractiveness for VRE's integration.

(i) In the model, the yearly cost of a power plant is calculated in the model by multiplying the electricity output times the PPA price. For heavy fuel oil powerplants, the electricity output compared to the installed capacity (expressed as a capacity factor) is only 8% (see appendix E). In reality, the time that the heavy fuel oil powerplant is not producing electricity but could be producing electricity must be compensated by the government with capacity payments (NEPRA, 2020). The costs for heavy fuel oil powerplants only based on the cost of produced electricity is therefore too low in the model. The same holds for other thermal powerplants, but those capacity factors are much higher. For the contracted market price both the cost for generated electricity and idle capacity are considered. The KPI contracted market price from the agent-based investment model only considers the cost for generated electricity. Therefore, the actual contracted market price will be higher.

(ii) Secondly, capacity payments reduce the attractiveness of VRE investment. With the obligation of capacity payments, NEPRA's goal is to match demand and supply such that all available production capacity is used. All unused available production capacity or idle capacity must be compensated. The intermittent nature of VRE complicates the match of supply to demand. With increased VRE capacity, the electricity market will have more moments when there is excess production capacity. Therefore, capacity payments for idle capacity will increase. Thus, VRE is less attractive for the electricity market because it increases capacity payments for idle capacity.

Variability of VRE is not explicitly included. The model uses the average capacity factor of VRE sources. This is an ill representation of the reality where these sources have daily and seasonal output variability (Heptonstall, 2021). Variability of VRE touch upon the trade-off between affordability and reliability. The market regulator NEPRA is responsible for this trade-off and would, therefore, probably change its price-setting behaviour. How the price-setting strategy change is outside of the scope of this research.

Generation types. Only coal, gas, wind, and solar is included. Hydro plays a large role and is expected to do so in the future (The World Bank, 2020b). The exclusion of hydro reduces the viability of the contracted market price and distort the energy mix results.

Storage. Storage of electricity is not included in this model while it is seen as an important factor in the energy transition. Excluding storage from the model is rooted in the decision to leave out the variability of VRE. Storage and variability of VRE go hand in hand as variability is solved with storage, but storage increase the price of VRE. The model focuses on actor behaviour, including VRE variability and storage shifts the focus to a much more technical model.

Coal price. In line with The World Bank 2020 model and contradicting the GoP's and NTDC's perspective, this model assumes that the coal price will not drastically decline when domestic coal is used for electricity generation. The coal price influences the business case of coal powerplants. Lower prices will lead to more investments in coal generation capacity.

Age and PPA price. The initial assets do not include the right age and a rough assumption on the PPA tariff. The restricted time of the research and the not readily available data prevented a complete mapping of the current fleet of powerplants. Including this would provide a more reliable starting value of the contracted market price.

Instant investment decision. In the model, investors update their investment decisions every year and can directly act on new information. In reality, when an investor decides to invest, it can take up to four years to receive all the permits and the PPA proposal. Thus, an investor must already make a significant investment to get a complete picture of the business case. Subsequently, the construction also takes between 1 – 4 years. Therefore, the model propagates a more rationally process of investment decisions than an actual investor face.

Discount values are not neutral. Discount value favours sources that have low initial investments and high OPEX over investments with high CAPEX and low OPEX. Therefore, the same discount value for four generation types results in a biased conclusion.

10.4.3. Validity of the used data sources

Most data sources used for the construction and parameterization of input values for the agent-based investment model do qualify as grey literature. This type of literature is not peer-reviewed, and information independence is not guaranteed. For this research, the primary sources of grey literature are reports published by The World Bank, IMF, International Energy Agency, and the National Electric Power Regulatory Authority (NEPRA). To prevent the usage of biased input data, all information from grey literature is benchmarked with other sources whenever possible.

Additionally, scientific papers on circular debt in Pakistan have limited citations and are published in low-impact journals. Appendix A.3. shows a selection of the used literature on circular debt in Pakistan with the included number of citations. During the research projects, research with low citations is avoided as much as possible. When this was not possible multiple sources were combined before making a statement.

11. CONCLUSION AND RECOMMENDATIONS

The research aims to provide insight into the effect of actor behaviour on circular debt in the context of the energy transition. This goal is fulfilled by performing a literature study to establish an analytical framework. Subsequently, the case study of the circular debt crisis in Pakistan, in the context of the energy transition, is conceptualised in a low-detail investment model using Agent-Based Modelling. The constructed model explores the effect of different behavioural scenarios of investors and the market regulator on the contracted market price of electricity and energy mix. Finally, the model results on the contracted market price are qualitatively linked to circular debt.

The chapter is structured as follows: in section 11.1, a synopsis of the research project is provided. This recalls the purpose of the research, the research gaps, and the research design. Second, in section 11.2, the four sub-questions are answered and brought together to answer the main research question in 11.3. The conclusions are put in perspective by discussing the societal and scientific contribution of the research in respectively 11.4 and 11.5. This chapter ends with recommendations for future research.

11.1 Synopsis research project

A reliable, accessible, and affordable electricity provision is crucial for economic development in emerging markets. It is the lifeblood of almost all processes in a country. A small business needs electricity for its machines to work, and large industrial processes require continuous power. Also, education and security depend on electricity for essential facilities such as (street)lighting. The stakes are high not only for businesses and consumers: a large set of stakeholders related to the transmission and distribution of electricity relies on the sector for their revenues and livelihoods.

For some emerging countries, ill-advised policies, unfortunate market development, and a bad starting position together with the already complex nature of the electricity sector caused circular debt to accumulate. *Circular debt is a self-reinforcing shortfall of revenue throughout the value chain that tends to look like a “vicious circle” without a proper solution.* The four leading drivers of the circular debt are (I) unpaid bills by consumers, (II) Transmission and distribution losses, (III) Tariff setting formula by NEPRA, and (IV) inefficient and expensive electricity production. This research focuses on the last driver: inefficient and expensive electricity production. Furthermore, the case of Pakistan’s current circular debt crisis is taken as subject of the research.

It is acknowledged by researchers to view, model and research the electricity system as a complex adaptive socio-technical system. In this complex adaptive system thinking, the behaviour of actors and interaction among actors is a starting point for understanding (long-term) emergent system-level behaviour. However, researchers and institutions studying circular debt have not yet applied complex adaptive thinking to study the circular debt crisis in Pakistan. More specifically, (1) it is unknown how to model the potential pathways of the electricity price, (2) how to integrate decision-making by investors and market regulators in an investment model and, (3) how to causally link the development of the electricity market price to circular debt.

This study follows two main steps to answer the aforementioned knowledge gaps: (i) an agent-based investment model is used to link actor behaviour to contracted market prices and Variable Renewable Energy (VRE) share, (ii) a qualitative analysis links the model results to the development of circular debt.

First, the agent-based investment model explores the impact of price-setting strategies of the market regulator and investment decisions of investors on two key performance indicators (a) the contracted market price and (b) the shares of variable renewable energy types in the total energy mix in Pakistan. Three types of private investors in generation capacity are distinguished based on the Diffusion of Innovation Theory: Development Finance Institutions (DFIs), progressive and conservative investors (Rogers, 1962). They act as front runners or followers in the energy transition. Furthermore, the market regulator NEPRA can show a progressive or conservation attitude towards renewable energy. Table 11 presents the four behavioural scenarios tested in the agent-based investment model during 25-year of the energy transition.

Table 11: 2x2 matrix shows the behavioural scenarios of market regulators and investors, resulting in four scenarios (A, B, C, D). The vertical axis shows the price-setting behaviour of the market regulator: progressive or conservative regarding VRE generation. The horizontal axis shows the attitude of investors: followers or front runners in the energy transition.

		Investor's attitude	
		Followers	Front runner
Market regulator renewable energy price-setting	Progressive	A	B
	Conservative	C	D

Second, the quantitative insights from the agent-based investment model are linked to the development of circular debt by using a qualitative approach that accounts for the complex dynamics of the electricity sector.

11.2 Answering the research sub-questions

Before an answer is formulated on the main research question, the research sub-questions are discussed.

Sub-question 1: What are the foremost causal drivers and interdependencies of the emergence and persistence of a circular debt crisis in the electricity sector of Pakistan?

Circular debt is a cash shortfall within the distribution companies that spread throughout the value chain. It tends to look like a “vicious circle” without a proper solution. The cash shortfall results from: (i) subsidy payment arrears by the government, and (ii) a mismatch between full-cost recovery and revenues realised by the distribution companies.

First, the cause of the subsidy payment arrears by the government of Pakistan is rooted in the retail pricing approach of Pakistan. In this approach, the cost recovery tariff is estimated by the market regulator NEPRA, and the end-user tariff is determined by the Ministry of Energy. The end-user tariff is the actual price consumers pay for their electricity to the distribution companies. The difference between the end-user tariff (what consumers actually pay) and NEPRA’s cost recovery tariff is filled with subsidies by the government called the ‘Tariff Differential Subsidy’ (TDS). However, the government of Pakistan cannot pay the full subsidy due to the precarious financial situation resulting in a payment arrear towards the distribution companies.

The second reason for debt accumulation is the mismatch between NEPRA’s cost recovery tariff and the actual revenues necessary to cover all costs. The actual tariff needed to cover all costs is called the full-cost recovery tariff. NEPRA considers three main elements for the calculation of the cost recovery tariff: (1) electricity procurement cost, (2) transmission cost with limited electricity losses, and (3) 100% bill recovery (i.e., all end-user paying their electricity bill to the distribution company). However, in reality, distribution companies have lower bill recovery levels (i.e., not all end-users pay their electricity bills) and higher electricity transmission losses. The costs that are higher than prescribed in NEPRA’s cost recovery tariff are unsubsidised, increasing the debt of distribution companies. Figure 37 provides a schematic overview of the reasons for revenue shortfall at the distribution companies.

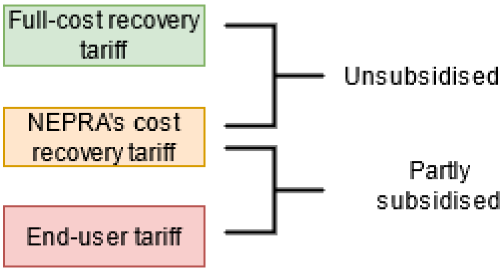

Figure 37: The subsidy arrear by the government is the result of the inability to pay subsidy surfacing from the mismatch between NEPRA's cost recovery tariff (orange), and the GoP regulated end-user tariff (red). The second reason for debt accumulation at distribution companies is a mismatch between the full-cost recovery tariff (green) and NEPRA's cost recovery tariff (yellow).

The drivers for the high tariff differential subsidy payments and resulting payment arrear are (i) inefficient and expensive electricity production and (ii) the formula to calculate NEPRA's cost recovery tariff. The drivers for the mismatch between full-cost recovery and the revenues realised by the distribution companies are (a) transmission and distribution losses and (b) non-payment of bills. Figure 38 provide an overview of how the drivers are related to each other.

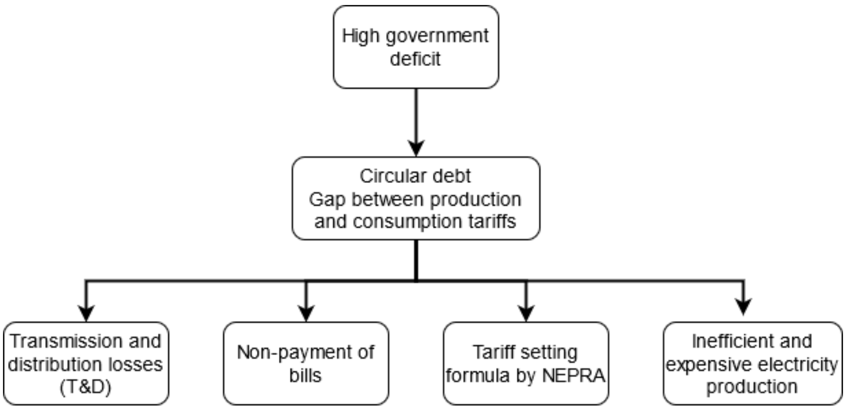

Figure 38: The flow chart presents the hierarchy of challenges in the circular debt crisis of Pakistan. The high government deficit leads to (i) subsidy payment arrears by the government, and (ii) a mismatch between full-cost recovery and revenues realised by the distribution companies which results in circular debt. Then circular debt is aggravated by four challenges: (1) transmission and distribution losses, (2) non-payment of bills, (3) tariff setting formula by NEPRA, and (4) inefficient and expensive electricity production. The focus of this research is on: inefficient and expensive electricity production.

Sub-question 2: How can the influence of investment decisions on the future electricity system in Pakistan be conceptualised?

A conceptual investment model of the electricity sector of Pakistan is designed based on the literature study and semi-structured interviews. Figure 39 shows this conceptual model as an input-output model. The basic principle of the investment model is a three-step cycle: (I) Pakistani market regulator NEPRA determines an electricity price per produced MWh, called the PPA-price, for each generation alternative (coal, gas, solar, wind), (II) investors calculate the Net Present Value (NPV) for each generation alternative based on their discount rate and invest in a generation type with a positive business case, (III) all investments together in the electricity market affect the two Key Performance Indicators (KPIs): contracted market price and the generation mix. The model starts in 2020, and the investment cycle repeats itself for each year for 25-years.

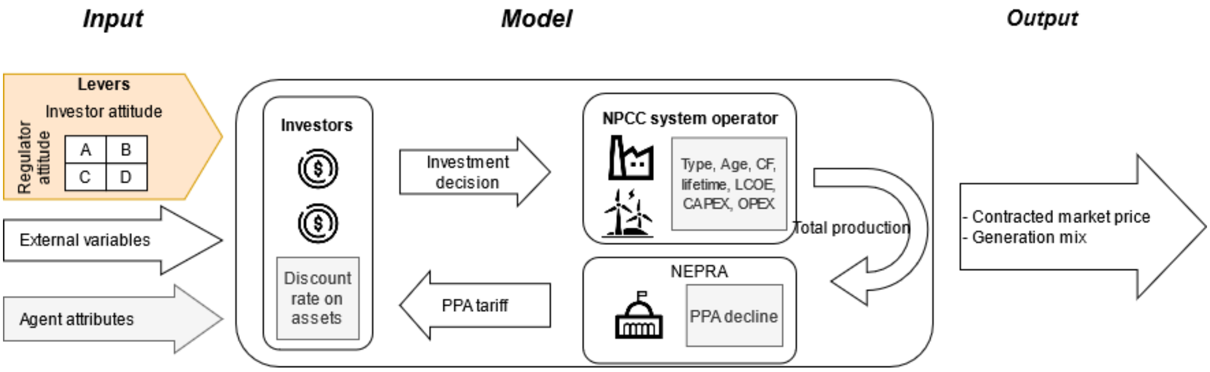

Figure 39: Input-output diagram of Pakistan's investment model. The orange input represents the 2x2 matrix based on the model levers that constitution the four behavioural scenarios. The white input arrow represents the external input variables. The grey arrow represents the agent attributes which are shown in the grey boxes in the model environment. The model has a three-step cycle: (I) NEPRA determines a PPA-tariff for each generation alternative, (II) investors calculate the net present value for each generation alternative, (III) all investments together in the electricity market update the two key performance indicators. The model's output is the key performance indicators 'contracted market price' and 'generation mix'.

The agents in the model exist of the market regulator NEPRA and three different private investors. The three private investors are distinguished based on the Diffusion of Innovation Theory and have a different degree of willingness to invest in variable renewable energy (Rogers, 1962). Ranked from most willing to least: Development Finance Institutions, progressive private investors, and conservative private investors. They act as front runners or followers in the energy transition. The market regulator NEPRA can show a progressive or conservation attitude towards renewable energy.

Sub-question 3: What is the effect of different investment and price-setting strategies on the future market price and energy mix of Pakistan?

Different investment and price-setting strategies significantly affect the future market price and the energy mix of Pakistan. In all four behavioural scenarios (Table 11 for overview scenarios), the contracted market price reduces significantly (Figure 40). For scenario A '*energy transition',* the cost reduction is the largest. In scenario A, both investors and the market regulator stimulate the business case of Variable Renewable Energy (VRE) by respectively their view on investment risk and price setting. In this scenario, VRE picks up from 5% to a share of ~80% and the electricity price declines from 83 US$/MWh to 46 US$/MWh in 2045. Scenario D '*status quo'* is the other extreme with a contracted market price of 64 US$/MWh and the lowest share of ~25% of VRE. In this scenario, the market regulator and investors are skewed to investments in thermal power.

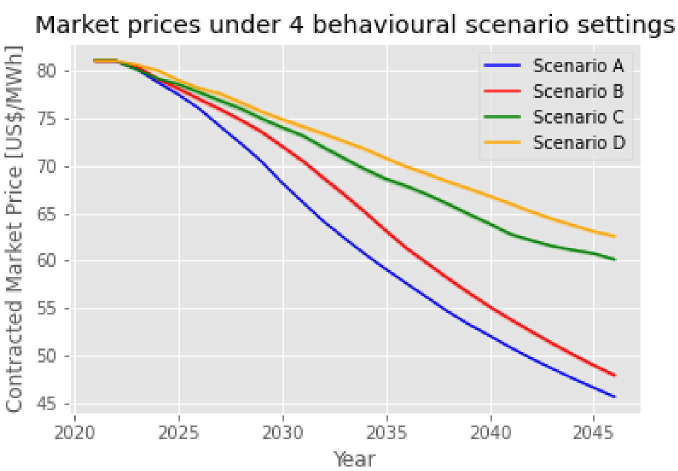

Figure 40: The contracted market price for the duration of the model in four scenarios. Scenario A and scenario D mark the boundary values for the contracted market price.

Analysing the behavioural experiments shows that the effect of price-setting strategy by the market regulator is larger than investments strategies of investors. When investors skew towards a positive attitude towards VRE, they can collectively lift renewable energy from a minority source (25%) to a serious alternative (35%). If the market regulator shows progressive behaviour, but investors are following (scenario B), the share of renewable energy grows from 5% to 70%. It should be borne in mind that the price-setting behaviour by the government is highly uncertain. Despite the uncertainty in the market and the regulator's future price-setting strategy, the market regulator can steer the future energy mix and, subsequently, the contracted market price. On the other hand, investors can adjust the direction of the energy transition but are bound to the government's strategy. These model results are in line with the literature and expert opinions expressed in semi-structured interviews.

The scenario experiments with six high impact /high uncertainty exogenous variables showed that the model is very sensitive to changes in the initial parameter settings. Therefore, the model results of this study should be viewed as possible futures that give a feeling for how the future could unfold.

Finally, in multiple scenarios experiments, it is observed that if the number of investments decreases in one of the VRE/thermal sources, investments in the source's counterpart (i.e., solar PV counterpart is wind, coal's counterpart is gas) compensate for this reduction. This effect is named the 'compensation by counterpart' effect. This effect results in a relatively stable contracted market price even though the share of one generation alternative changes sharply.

Sub-question 4: What is the implication of the future electricity system on the development of circular debt in Pakistan?

The agent-based investment model provides insight into the effect of behavioural strategies on the contracted market price. To answer the fourth sub-question, quantitative insight on contracted market price is linked to the development of circular debt. From the qualitative analysis, it became clear that no conclusion can be drawn on the degree of causality between lower contracted market price and an improved circular debt position. The degree of causality is unclear because the savings in the electricity system can be redistributed in multiple other ways than the reduction of circular debt. It can also be used for, lower consumer prices and reduced sovereign debt.

The decision-making process of redistributing savings in the electricity sector happens in a political environment influenced by many actors and factors. This political environment blurs the causality between contracted market price and circular debt. However, the causality only becomes visible when the contracted market price change significantly. Large shifts in contracted market price and circular debt were observed during the 1998 and 2011 currency crises. Small changes in contracted market prices are unlikely to be directly visible in the circular debt position due to the sticky political decision-making process with time-consuming procedures and many involved political entities.

Additional to the just mentioned delay in the impact of small changes in contracted market prices on circular debt is the observation from sub-question three that it takes at least 5-years before investments in variable renewable energy impact the contracted market price. If both observations are brought together, it can be concluded that the effect of VRE integration on circular debt takes at least 5-years to materializes and is delayed due to political stickiness.

The slow impact of variable renewable energy integration on circular debt leads to a mismatch between the short-term circular debt problem and the more extended period required for substantial VRE integration. In the short term, the current circular debt crisis needs an imminent response to prevent repeating the 1998 and 2011 currency crises. Back then, the results were large currency devaluations, civil unrest, and long load shedding periods. In the long-term, large-scale integration of VRE will bring down the contracted market price and therefore reduce circular debt. However, large-scale integration of VRE is a multi-decade project. It requires major refurbishment of the electricity sector and its policy framework. It will affect all aspects of Pakistan's energy supply, ranging from high-level geopolitics to national infrastructure topology and market operations to local-level governance restructuring (Scholten et al. 2018, 5). The question is how to bridge the short-term and long-term chasm.

Even though large-scale integration of VRE is not deemed a realistic solution for the current circular debt crisis, focus on VRE projects is needed now to prevent future circular debt crises. The rationale behind acting now on VRE integration revolves around three insights from the literature review and case study: (1) the electricity sector of Pakistan is a complex adaptive socio-technical system characterised by path dependence (section 2.1; Nikolic, 2009; Personal communication, April 15 2021, Appendix C.3), (2) the circular debt crisis is a policy window for large scale change (IMF, 2006), and (3) the government of Pakistan is sensitive for VRE success stories (personal communication, June 17 2021, Appendix C.5).

The path-dependent nature of the electricity system makes it difficult for the system to make a paradigm shift towards a large-scale VRE-based system in the short term. However, the imminent circular debt crisis and the global energy transition resulting in falling VRE costs provides a policy window to deviation from the historical path. When VRE projects (production and transmission) are included in the package of policy reforms, a bottom-up transition could emerge that enhances change towards large scale implementation of VRE. Successful VRE projects and grid adaptions have a cascading effect on the system components relevant to large-scale VRE adoption. Important components in this matter are the expertise and commitments of policymakers, the public opinion, and investors' risk assessment concerning VRE. The long-term influence of successful VRE projects is partly contingent upon the government's sensitivity to success stories and the continuation of VRE cost decline. This reasoning is congruent with the complex system thinking that bottom-up changes lead to emergent system-level change through a complex non-linear process of interactions.

In summary, large-scale integration of VRE is not a feasible solution for the present circular debt crisis but is a vital long-term driver to prevent the repetition of another circular debt crisis. Realising successful VRE projects paves the way for a large-scale renewable energy integration that sustains long-term prevention of new circular debt crises. Therefore, the short-term solutions to the current circular debt crisis should include investments in VRE projects.

11.3 Answering the main research question

How will different investment decisions and prices settings strategies, within the energy transition context, effect circular debt?

The results of the agent-based investment model showed that in all scenarios, the electricity price declines. The largest price reduction is observed in the scenarios where investment decisions and price-settings strategies favour VRE investments. The market regulators' price-setting strategy has a larger influence on the electricity price than investors investment attitude. The current pathway by the market regulator leans towards a conservative price setting. This chosen direction is hard to change as the electricity system is path-dependent by nature. If the conservative attitude continues to 2045, VRE will remain the minority generation alternative. However, the circular debt crisis and the global energy transition resulting in falling VRE costs push large direction changes. This could shift the behaviour of the market regulator towards a progressive attitude leading to a significant share of VRE in 2045.

In addition, this study's qualitative research confirms the *positive causal relationship* between contracted market prices and circular debt of previous studies. However, no conclusions can be drawn about the *degree of causality* between lower contracted market prices and an improved circular debt position.

Finally, the analysis also shows a mismatch between the short-term problem of circular debt and the long-term solution of integrating renewable energy. Integration of VRE is not a solution for the current circular debt crisis but a vital long-term driver to prevent the repetition of circular debt crises. It is nevertheless essential to invest in VRE projects in the short term to create success stories that influence the attitude of the market regulator and investors.

11.4 Recommendation for stakeholders

The insights gathered from this research is translated to recommendations for the Pakistani government, market regulator NEPRA and the Dutch Development bank FMO. The focus is not so much on the technical feasibility of renewable energy but on feasible behavioural changes of the various stakeholders within the political context of the circular debt crisis.

The model results show that the behavioural strategy of NEPRA and investors have a large influence on the development of the generation mix and the associated contracted market price. Sub-question 4 discussed that successful VRE projects influence these behavioural attitudes. Therefore, Dutch Development Bank FMO is recommended to support and finance VRE generation capacity projects. Also, financing transmission grid and electricity storage projects aimed at increasing grid efficiency and the capacity to sustain VRE is beneficial to create success stories that grid transformation is feasible.

Second, the Government of Pakistan should consider prioritising the shortening and smoothing of the investment period before a power purchase agreement proposal is provided by NEPRA. This reduces the upfront risk for project developers, increases the willingness to invest in VRE projects, and reduces risk margins. With more competition for VRE projects, NEPRA can select more competitive project proposals for a selected VRE site.

Third, market regulator NEPRA could increase VRE investments by mandating project developers to propose VRE sites. Currently, project developers are restricted to the number of sites selected by NEPRA. By allowing project developers to propose VRE sites, NEPRA becomes more flexible in ramping up VRE investments if the demand for VRE capacity increases.

Finally, it is advised to scale down the capacity payment clause in the power purchase agreement contracts in anticipation of more VRE integration. The capacity payment clause obliges the single buyer to buy electricity from a power plant if it can produce electricity. This so-called 'take-or-pay' obligation is regardless of the availability of other cheaper sources. Therefore, the capacity payments clause brings a 'lock-in' to continue with thermal generation for at least the contract duration of a new thermal powerplant. As capacity payment contracts are for up to 30-years, it could very well be that the electricity sector pays for expensive electricity production in the future when cheaper alternatives are available.

11.4 Societal contribution

The study focuses on a problem that adversely affects many people's day-to-day lives. Electricity is vital for developing an economy, poverty reduction and the reduction of income inequality (Sarkodie, 2020). Circular debt paralyzes new investments in the electricity sector and therefore hampers economic growth.

This research shows that solving the circular debt crisis in the long term goes hand-in-hand with investments in renewable energy. Therefore, the sustainable development goals of affordable and clean energy (SDG 7), reduced inequality (SDG 10) and climate action (SDG 13) are all brought together. Affordable and clean energy is directly measured in the study with *contracted market price* and *share of generation alternative in the energy mix* as Key Performance Indicators

11.5 Scientific contribution

This research applies complex adaptive socio-technical thinking to a single buyer market in Pakistan with the aim to study the effect of behaviour on circular debt. More specifically, this study proposes novel insight in three key elements: (1) the possibility to model the potential pathways of the electricity price using an agent-based investment model, (2) integration of decision-making behaviour of a market regulator and investors in an agent-based investment model a single-buyer market structure, and (3) link quantitative model results to qualitative research.

Currently, models used to explore future states of the electricity system of emerging markets are based on optimisation models. An example is a study on integrating renewable energy in Pakistan by The World Bank (2020a). These studies are essential reference points for policy makers and business decisions. However, the electricity system is a complex adaptive socio-technical system. This implies that the system behaviour emerges from bottom-up actor behaviour and that decision-making by actors is according to the new institutional economic theory of bounded rationality, imperfect information, and imperfect foresight (Groenewegen, 2004; Kraan et al., 2018; Chappin et al., 2017).

This research presents an agent-based investment model that explores the influence of price-setting and investment strategies by the market regulator and investors on the energy mix and contracted market price. By presenting this, the research showed that it is possible to explore the development of the generation mix and contracted market price over 25 years using a complex adaptive socio-technical system view. The ABM approach contrasts with the optimisation models currently used by policy makers and business developers that show what ideally is possible when actors behave rationally, with full information and foresight (Kraan et al., 2018).

Secondly, two theories are frequently applied for the conceptualisation of economic decision-making: neo-classical economics and institutional economics. Neo-classical economics looks at humans as rational actors with perfect information and foresight (Groenewegen, 2004). The optimisation model of The World Bank (2020b) is based on this economic decision-making theory. However, Kraan et al. (2018) suggest that adopting the institutional economic viewpoint is more suitable for conceptualising decision-making in a complex adaptive system.

In this study, the conceptualisation of the market regulator and investors' behaviour showed that applying the institutional economic viewpoint is possible for a single-buyer market structure. Therefore, this research extends the applicability of institutional economic decision-making in electricity sector investment models from a wholesale perspective, presented by Kraan et al. (2018), to a single-buyer market structure. The difference between a wholesale and single-buyers investment model is adding a market regulator as a price-setting entity in the single-buyer market structure (Course reader, SEN1522 Electricity and Gas, CoSEM master, TU Delft, 2019). For the translation to a single-buyer market structure, a new method to conceptualise the price-setting behaviour of a market regulator is presented. This led to a novel way to conceptualise the investment model and the setup of different behavioural scenarios.

Finally, circular debt is a broad challenge where many (sub) systems interact which each other in a complex pattern. This research showed that despite the extensive complexity, linking investment and price-setting behaviour to the development of circular debt is possible by combining quantitative model results with qualitative insights.

11.6 Recommendations for future research

During this study, several interesting topics for further research are identified.

First, this research used a qualitative approach to confirm a positive causality between the contracted market prices and circular debt. However, understanding of the degree of causality is still lacking. A literature study, additional modelling study or qualitative research can help to further explore the degree of this causal link, which is vital to motivate the importance of investments in low-cost electricity production.

Second, expanding the model with a daily or weekly production pattern of VRE sources attuned to the country’s production and demand characteristics would be valuable. It enables the possibility to include capacity payments in the model. These capacity payments could then be used for a feedback loop with the price-setting strategy of the market regulator. This addition would provide interesting insights for policy making by the Pakistani government and the development of the contracted market price.

Third, a progression of this work is to include the integration cost of VRE in the conceptualisation of the market regulator. Based on the literature study, it is expected that the additional cost of VRE, which is currently not included in the Levelized Cost of Electricity in the model, influences the market regulator's price-setting behaviour. The significance of this influence remains, however, unclear.

Finally, the conceptualisation of the Pakistan electricity sector in terms of generation sources does not consider hydropower and electricity storage. Hydropower is a major source that shapes the electricity price and energy mix, now and in the future (The World Bank, 2020b). Neglecting hydropower reduce the completeness of the model results. Hydropower is not included in this study because development is led by the public entity: Water and Power Development Authority. This research is demarcated to private investors. Furthermore, electricity storage will most likely play a prominent role in the energy transition. Insight into the effect of storage capacity on the contracted market price of electricity is valuable for investment decisions and electricity market development. Electricity storage is a technology currently not applied in Pakistan, therefore, reliable data is lacking.

REFERENCES

ACWA Power (2017). Renewable Energy A Compelling Value Proposition In the fossil fuel capital. Japan Renewable energy institute 6th annual conference.

Aldersey-Williams, J., & Rubert, T. (2019). Levelised cost of energy – A theoretical justification and critical assessment. Energy Policy, 124(February 2018), 169–179. https://doi.org/10.1016/j.enpol.2018.10.004

Arowolo, W., & Perez, Y. (2020). Market reform in the Nigeria power sector: A review of the issues and potential solutions. Energy Policy, 144(May), 111580. https://doi.org/10.1016/j.enpol.2020.111580

Asian Development Bank (2019). Report and Recommendations of the President to the Board of Directors. Project number 53165-001. ADB, Mandaluyong, Philippines.

Bacon, R. (2019). Learning from Power Sector Reform: The Case of Pakistan. Policy Research Working Paper; No. 8842. World Bank, Washington, DC. https://openknowledge.worldbank.org/handle/10986/31667

Bacon, R.W., Besant-Jones, J. (2002). *Global Electric Power Reform, Privatization, and Liberalization of the Electric Power industry in Developing Countries.* Energy and Mining Sector Board discussion paper series: Paper no.2 (June 2002) Washington D.C.: World Bank Group. http://documents.worldbank.org/curated/en/226491468780869282/Global-electric-power-reform-privatization-and-liberalization-of-the-electric-power-industry-in-developing-countries

Barnard, P. L., Dugan, J. E., Page, H. M., Wood, N. J., Hart, J. A. F., Cayan, D. R., Erikson, L. H., Hubbard, D. M., Myers, M. R., Melack, J. M., & Iacobellis, S. F. (2021). Multiple climate change-driven tipping points for coastal systems. *Scientific Reports*, *11*(1). https://doi.org/10.1038/s41598-021-94942-7

Borshchev, A., & Filippov, A. (2004). From system dynamics and discrete event to practical agent based modeling: reasons, techniques, tools. In *Proceedings of the 22nd international conference of the system dynamics society* (Vol. 22, pp. 25-29). Oxfort.

BP (2020). Statistical Review of World Energy. 69th edition

Bruck, N. (1998). The role of development banks in the Twenty-First Century. Journal of Emerging Markets 3, 39-67

Cesaro, Z., Ives, M., Nayak-Luke, R., Mason, M., & Bañares-Alcántara, R. (2021). Ammonia to power: Forecasting the levelized cost of electricity from green ammonia in large-scale power plants. *Applied Energy*, *282*, 116009. https://doi.org/10.1016/j.apenergy.2020.116009

Correljé, A.F., & De Vries, L. J. (2008). Hybrid electricity markets: The problem of explaining different patterns of restructuring. In *Competitive Electricity Markets* (pp. 65-93). Elsevier.

Cui, R.Y., et al. (2019) Quantifying operational lifetimes for coal power plants under the Paris goals. Nature communications, 10(1), 1-9.

De Bruijn, H., & Herder, P. M. (2009). System and actor perspectives on sociotechnical systems. *IEEE Transactions on systems, man, and cybernetics-part A: Systems and Humans*, *39*(5), 981-992.

European Development Finance Institutions (EDFI) (2019). What is a DFI? Retrieved from https://www.edfi.eu/about-dfis/what-is-a-dfi/

European Environment Agency (2015). EN19 Efficiency of conventional thermal electricity production. Retrieved from https://www.eea.europa.eu/data-and-maps/indicators/en19-efficiency-of-conventional-thermal-1

FMO – the Dutch Entrepreneurial Development Bank (2019, September 13). Doing makes the Difference [Video]. Youtube. https://www.youtube.com/watch?v=zEoYRV5X_9E

Glachant, J. M., & Finon, D. (2000). Why do the European Union's electricity industries continue to differ? A new institutional analysis. In: In: C. Ménard, ed.: *Institution, contracts and organizations: perspectives from new institutional economics.* London: Edward Elgar.

Global Wind Atlas (n.d.). Global Wind Atlas Pakistan. Retrieved May 20, 2021, from https://globalwindatlas.info/

Groenewegen, J. (2004). Inzichten uit de institutionele economie. Maandblad Voor Accountancy en Bedrijfseconomie. 78. 515-523. 10.5117/mab.78.12783.

Haselip, J., & Hilson, G. (2005). Winners and losers from industry reforms in the developing world: Experiences from the electricity and mining sectors. Resources Policy, 30(2), 87–100. https://doi.org/10.1016/j.resourpol.2004.10.001

Haselip, J., Dyner, I., & Cherni, J. (2005). Electricity market reform in Argentina: Assessing the impact for the poor in Buenos Aires. Utilities Policy, 13(1), 1–14. https://doi.org/10.1016/j.jup.2004.03.001

Hazeu, C.A. (2007). Institutionele Economie: een optiek op organisatie- en sturingsvraagstukken (2nd ed.). Coutinho.

Heller, T. C., & Victor, D. G. (2004). *A political economy of electric power market restructuring: introduction to issues and expectations* (Vol. 1). working paper.

Heptonstall, P. J., & Gross, R. J. K. (2021). A systematic review of the costs and impacts of integrating variable renewables into power grids. Nature Energy, 6(1), 72–83. https://doi.org/10.1038/s41560-020-00695-4

Huenteler, J. (2014). International support for feed-in tariffs in developing countries—A review and analysis of proposed mechanisms. *Renewable and Sustainable Energy Reviews*, 39, 857–873. https://doi.org/10.1016/j.rser.2014.07.124

IMF, 2003, External Debt Statistics: Guide for Compilers and Users – Appendix III, Glossary, IMF, Washington DC.

International Energy Agency (2020), Projected Costs of Generating Electricity 2020, IEA, Paris https://www.iea.org/reports/projected-costs-of-generating-electricity-2020

International Finance Group (2016). A Solar Developer's Guide to Pakistan. Retrieved from https://www.ifc.org/wps/wcm/connect/topics_ext_content/ifc_external_corporate_site/sustainability-at-ifc/publications/p_report_solardevelopersguidetopakistan

International Monetary Fund (2006). *Quasi-Fiscal Deficit and Energy Conditionality in Selected CIS Countries*. IMF Working Paper 06/43. International Monetary Fund, Washington, DC.

International Monetary Fund (2019). PAKISTAN: FIRST REVIEW UNDER THE EXTENDED ARRANGEMENT UNDER THE EXTENDED FUND FACILITY AND REQUEST FOR MODIFICATION OF PERFORMANCE CRITERIA—PRESS RELEASE; STAFF REPORT;

AND STATEMENT BY THE EXECUTIVE DIRECTOR FOR PAKISTAN. Retrieved from https://www.imf.org/en/Publications/CR/Issues/2019/12/20/Pakistan-First-Review-Under-the-Extended-Arrangement-Under-the-Extended-Fund-Facility-and-48899

International Monetary Fund (2020). World Economic Outlook: A Long and Difficult Ascent. International Monetary Fund, Washington, DC. https://www.imf.org/en/Publications/WEO/Issues/2020/09/30/world-economic-outlook-october-2020

International Monetary Fund (n.d.). IMF DATAMAPPER. Retrieved March 20, 2021, from https://www.imf.org/external/datamapper/profile/PAK

International Renewable Energy Agency (2018). Global Energy Transformation: A roadmap to 2050. International Renewable Energy Agency, Abu Dhabi.

Jenkins, K., McCauley, D., Heffron, R., Stephan, H., & Rehner, R. (2016). Energy justice: A conceptual review. Energy Research & Social Science, 11, 174–182. https://doi.org/10.1016/j.erss.2015.10.004

Joskow, P. L. (2011). Comparing the Costs of Intermittent and Dispatchable Electricity Generating Technologies. American Economic Review, 101(3), 238–241. https://doi.org/10.1257/aer.101.3.238

Kamran, M. (2018). Current status and future success of renewable energy in Pakistan. Renewable and Sustainable Energy Reviews, 82(September 2016), 609–617. https://doi.org/10.1016/j.rser.2017.09.049

Kessides, I. N. (2013). Chaos in power: Pakistan's electricity crisis. Energy Policy, 55, 271–285. https://doi.org/10.1016/j.enpol.2012.12.005

Kraan, O., Kramer, G. J., & Nikolic, I. (2018). Investment in the future electricity system - An agent-based modelling approach. Energy, 151, 569–580. https://doi.org/10.1016/j.energy.2018.03.092

Mahmood, A., Javaid, N., Zafar, A., Ali Riaz, R., Ahmed, S., & Razzaq, S. (2014). Pakistan's overall energy potential assessment, comparison of LNG, TAPI and IPI gas projects. Renewable and Sustainable Energy Reviews, 31, 182–193. https://doi.org/10.1016/j.rser.2013.11.047

Marshall, T. (2015). Prisoners of Geography: Ten Maps that Tell You Everything You Need To Know About Global Politics (Rev. ed.). Elliot & Thompson

Mayr, F. (2014). The Vast Potential of Hybrid Renewable Energy Solutions for Unlocking New Solar and Wind Markets. Apricum: a cleantech advisor. Retrieved on 01/07/2021 from https://apricum-group.com/vast-potential-hybrid-renewable-energy-solutions-unlocking-new-markets/?cn-reloaded=1

National Electric Power Regulatory Authority (2006). State of Industry Report 2006. NEPRA, Islamabad, Pakistan. https://nepra.org.pk/publications/State%20of%20Industry%20Reports.php

National Electric Power Regulatory Authority (2020). State of Industry Report 2020. NEPRA, Islamabad, Pakistan. https://nepra.org.pk/publications/State%20of%20Industry%20Reports.php

National Renewable Energy Laboratory (2020). ATB Electricity Data Overview. Retrieved May 05, 2021, from https://atb.nrel.gov/electricity/2020/index.php

NEPRA (z.d.). Tariff Generation IPPs. Geraadpleegd op 20 juli 2021, van https://nepra.org.pk/tariff/Generation%20IPPs.php

Nikolic, I. (2009). *Co-Evolutionary Method For Modelling Large Scale Socio-Technical Systems Evolution* [Doctoral dissertation, Delft University of Technology]. https://repository.tudelft.nl/.

Nikolic, I., Lukszo, Z., Chappin, E., Warnier, M., Kwakkel, J., Bots, P. & Brazier, F. (2019). Guide for good modelling practice in policy support. TUD / TPM. doi: 10.4233/uuid:cbe7a9cb-6585-4dd5-a34b-0d3507d4f188

Our World in Data (2020). Why did renewables become so cheap so fast? And what can we do to use this global opportunity for green growth?. Retrieved May 10, 2021, from https://ourworldindata.org/cheap-renewables-growth

Pollitt, M. (2008). *Electricity reform in Argentina: Lessons for developing countries.* Energy Economics, 30(4), 1536–1567. https://doi.org/10.1016/j.eneco.2007.12.012

Pueyo, A. (2018). What constrains renewable energy investment in Sub-Saharan Africa? A comparison of Kenya and Ghana. World Development, 109, 85–100. https://doi.org/10.1016/j.worlddev.2018.04.008

Qazi, U., & Jahanzaib, M. (2018). An integrated sectoral framework for the development of sustainable power sector in Pakistan. Energy Reports, 4, 376–392. https://doi.org/10.1016/j.egyr.2018.06.001

Qudrat-Ullah, H. (2015). Independent Power (or pollution) producers? Electricity reforms and IPPs in Pakistan. Energy, 83, 240-251. https://doi.org/10.1016/j.energy.2015.02.018

Rauf, O., Wang, S., Yuan, P., & Tan, J. (2015). An overview of energy status and development in Pakistan. Renewable and Sustainable Energy Reviews, 48, 892–931. https://doi.org/10.1016/j.rser.2015.04.012

Redaelli, S. (2019). Pakistan at 100 : From Poverty to Equity. World Bank, Washington. https://openknowledge.worldbank.org/handle/10986/31409.

Rogers, E.M. (1962). Diffusion of innovation. New York Free Press of Glencoe.

Sadiqa, A., Gulagi, A., & Breyer, C. (2018). Energy transition roadmap towards 100% renewable energy and role of storage technologies for Pakistan by 2050. Energy, 147, 518–533. https://doi.org/10.1016/j.energy.2018.01.027

Sahir, M. H., & Qureshi, A. H. (2007). Specific concerns of Pakistan in the context of energy security issues and geopolitics of the region. Energy Policy, 35(4), 2031–2037. https://doi.org/10.1016/j.enpol.2006.08.010

Sarkodie, S. A., & Adams, S. (2020). Electricity access, human development index, governance and income inequality in Sub-Saharan Africa. *Energy Reports*, *6*, 455–466. https://doi.org/10.1016/j.egyr.2020.02.009

Scholten, D. (Red.). (2018). The Geopolitics of Renewables. *Lecture Notes in Energy*. Published. https://doi.org/10.1007/978-3-319-67855-9

Shaikh, F., Ji, Q., & Fan, Y. (2015). The diagnosis of an electricity crisis and alternative energy development in Pakistan. Renewable and Sustainable Energy Reviews, 52, 1172–1185. https://doi.org/10.1016/j.rser.2015.08.009

Solargis (2021). Solar Resource maps of Pakistan. © *2020 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis. Retrieved May 20, 2021, from https://solargis.com/maps-and-gis-data/download/pakistan*

Sönnichsen, N. (2020). Total capacity of electricity installed in the Netherlands in 2018, by type. Statista. https://www.statista.com/statistics/1189565/netherlands-installed-electricity-capacity-by-type/

Subramanian, A., Gundersen, T., & Adams, T. (2018). Modeling and Simulation of Energy Systems: A Review. Processes, 6(12), 238. https://doi.org/10.3390/pr6120238

TRANSFORM (2018). High-Efficiency, Low-emissions Coal Plants: Come HELE or High water. Retrieved from https://www.ge.com/power/transform/article.transform.articles.2018.mar.come-hele-or-high-water#

Ueckerdt, F., Brecha, R., & Luderer, G. (2015). Analyzing major challenges of wind and solar variability in power systems. Renewable Energy, 81, 1–10. https://doi.org/10.1016/j.renene.2015.03.002

Ueckerdt, F., Hirth, L., Luderer, G., & Edenhofer, O. (2013). System LCOE: What are the costs of variable renewables? Energy, 63, 61–75. https://doi.org/10.1016/j.energy.2013.10.072

United Nations Office for the Coordination of Humanitarian Affairs [OCHA] (n.d.). Pakistan Maps and Infographics. Retrieved March 20, 2021, from https://www.unocha.org/Pakistan

Valasai, G. Das, Uqaili, M. A., Memon, H. U. R., Samoo, S. R., Mirjat, N. H., & Harijan, K. (2017). Overcoming electricity crisis in Pakistan: A review of sustainable electricity options. *Renewable and Sustainable Energy Reviews*, *72*(November 2015), 734–745. https://doi.org/10.1016/j.rser.2017.01.097

Van Dam, K.H., Nikolic, I. & Lukszo, Z. (2013). Agent-Based Modelling of Socio-Technical Systems. Springer US. doi: 10.1007/978-94-007-4933-7

Vox (2020). *4 astonishing signs of coal's declining economic viability*. Retrieved May 10, 2021, from https://www.vox.com/energy-and-environment/2020/3/14/21177941/climate-change-coal-renewable-energy

Waldrop, M. M. (1992). *Complexity: The emerging science at the edge of order and chaos.* Simon and Schuster, New York, 1992.

Williamson, J., & Ghanadan, R. (2006). Electricity reform in developing and transition countries: A reappraisal. Energy, 31(6–7), 815–844. https://doi.org/10.1016/j.energy.2005.02.008

Williamson, O.E. (1998). Transaction cost economics how it works; where it is headed., De Economist, 146(1), 23-58

World Bank (2020b). Variable Renewable Energy Integration and Planning Study. Pakistan Sustainable energy Series. The World Bank, Washington, DC. https://openknowledge.worldbank.org/handle/10986/34586

World Bank Group (2020a). Rethinking Power Sector Reform in the Developing World. Sustainable Infrastructure Series Washington, DC: World Bank.

World Bank Group (2020b). Variable Renewable Energy Integration and Planning Study. Pakistan Sustainable Energy Series. Washington, DC: World Bank.

WRI India (2021). *Renewable Energy to Responsible Energy: A Call to Action.* https://wri-india.org/events/renewable-energy-responsible-energy-call-action

Zameer, H., & Wang, Y. (2018). Energy production system optimisation: Evidence from Pakistan. Renewable and Sustainable Energy Reviews, 82(September 2017), 886–893. https://doi.org/10.1016/j.rser.2017.09.089

Zhang, Y. F., Parker, D., & Kirkpatrick, C. (2007). Electricity sector reform in developing countries: an econometric assessment of the effects of privatization, competition and regulation. Journal of Regulatory Economics, 33(2), 159–178.

APPENDIX

Appendix A: Literature review approach

The systematic literature review consists of two steps database search and forward snowballing.

A.1. Database search

The database search is conducted using a keyword search in Scopus Scientific database (Elsevier, n.d.). The keywords query aims to map the current scientific knowledge of Pakistan's circular debt crisis. The search was conducted on the 2nd of December 2020 and consist of the following keywords search:

- TITLE-ABS-KEY("circular debt" AND "Pakistan")

The search query delivered 19 results. More searches where performed to verify whether this search query bring forth all relevant papers. The keyword 'Pakistan' was removed and it resulted in the same 19 results. The search was filtered on English languages. After this all abstract where read to decide which are relevant for the literature review. The selection was based on the following criteria:

- Research on causes of circular debt
- Research on solutions of circular debt

Selection by abstract led to a final selection of nine papers.

A.2. Forward snowballing

To explore whether there are more relevant papers forward snowballing was used. It was conducted on the most cited paper of Kessides (2013). Within the citations, the results were limited to articles, and this resulted in 60 papers. The title of these papers where scanned and the selection was based on:

- Does the study specifically include Pakistan?
- Does it address one of the main challenges in Pakistan's energy sector related to the circular debt situation?
- Is the paper of sufficient quality?

After reading the abstracts using the above-mentioned criteria, nine papers were selected from citations of Kessides (2013).

A.3. Final set of papers

The previous steps retrieved a total of eighteen papers. Figure 1 and Table 1 provides an overview.

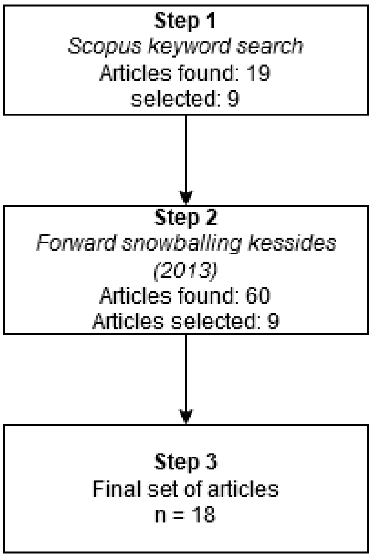

Figure 41: Literature search results

Table 12: The Overview of selected papers

Author, date	Relevant focus and findings	Method of finding paper	Citations
Ali et al. (2020)	Solutions to mitigate financial debt by increasing the share of renewables and inexpensive energy	Database search	0
Kamran et al (2019)	Overview of power sector since 1947, energy policies since 1994 and recent renewable energy policy	Database search	3
Zameer and Wang (2018)	Scenario analysis to explore optimal energy mix and minimise electricity cost and circular debt	Database search	39
Mohiuddin, O. (2016)	Recognise the disadvantage of the dependence of fossil fuel and propose an alternative with low-cost agricultural waste	Database search	15
Shaikh (2015)	Conclude that fuel diversification with alternative energy sources is a solution for circular debt	Database search	51
Imran and Amir (2015)	Paper provides a strategy to efficiently utilise available generation capacity	Database search	14
Mahmood (2014)	Review of Pakistan's energy sector including energy imports and energy potential of RES	Database search	49
Khan (2013)	Model for detection of line losses	Database search	1
Kessides (2013)	Paper analyses the problem confronting Pakistan's electricity sector and identifies policy responses	Database search	99
Azam et al. (2020)	Relationship between electricity supply and economic growth	Forward snowballing Kessides (2013)	5

Yasmeen et al. (2019)	Effect of oil price volatility on real sector growth	Forward snowballing Kessides (2013)	10
Shah et al. (2019)	Opportunities, barriers, and policy recommendations for 100% renewables	Forward snowballing Kessides (2013)	10
Kazmi et al. (2019)	Electricity load shedding	Forward snowballing Kessides (2013)	3
Rehman et al. (2018)	Rural and urban population access to electricity	Forward snowballing Kessides (2013)	10
Rehman and Deyuan (2018)	Relationship between electricity access energy use, population growth and economic growth	Forward snowballing Kessides (2013)	11
Jamil (2018)	Electricity theft	Forward snowballing Kessides (2013)	8
Qazi et al. (2018)	Sectoral framework for the development of sustainable power sector	Forward snowballing Kessides (2013)	7
Sadiqa et al. (2018)	Energy transition roadmap towards 100% renewables	Forward snowballing Kessides (2013)	39

Appendix B: System identification and decomposition

The first part of this appendix engages in the translation of the real-world system into a demarcated conceptual view. The resulting demarcated causal relations diagram is the product of the intermediate step that depict the full system into a causal relations diagram. Demarcating is the first step towards a conceptual view suitable for Agent-Based modelling. The second part of the chapter provides a list of agents, their properties, their actions, and their interactions (van Dam et al. 2013, 81).

B.1. Full system causal relations diagram

The main research questions that guide this research is the influence of investment in variable renewable energy (solar and wind) on circular debt in Pakistan. The previous chapter described the factors in a quantitative manner by using a literature study. This section isolated the most important factors and connected those factors in a full system causal relations diagram depicted in figure 1.

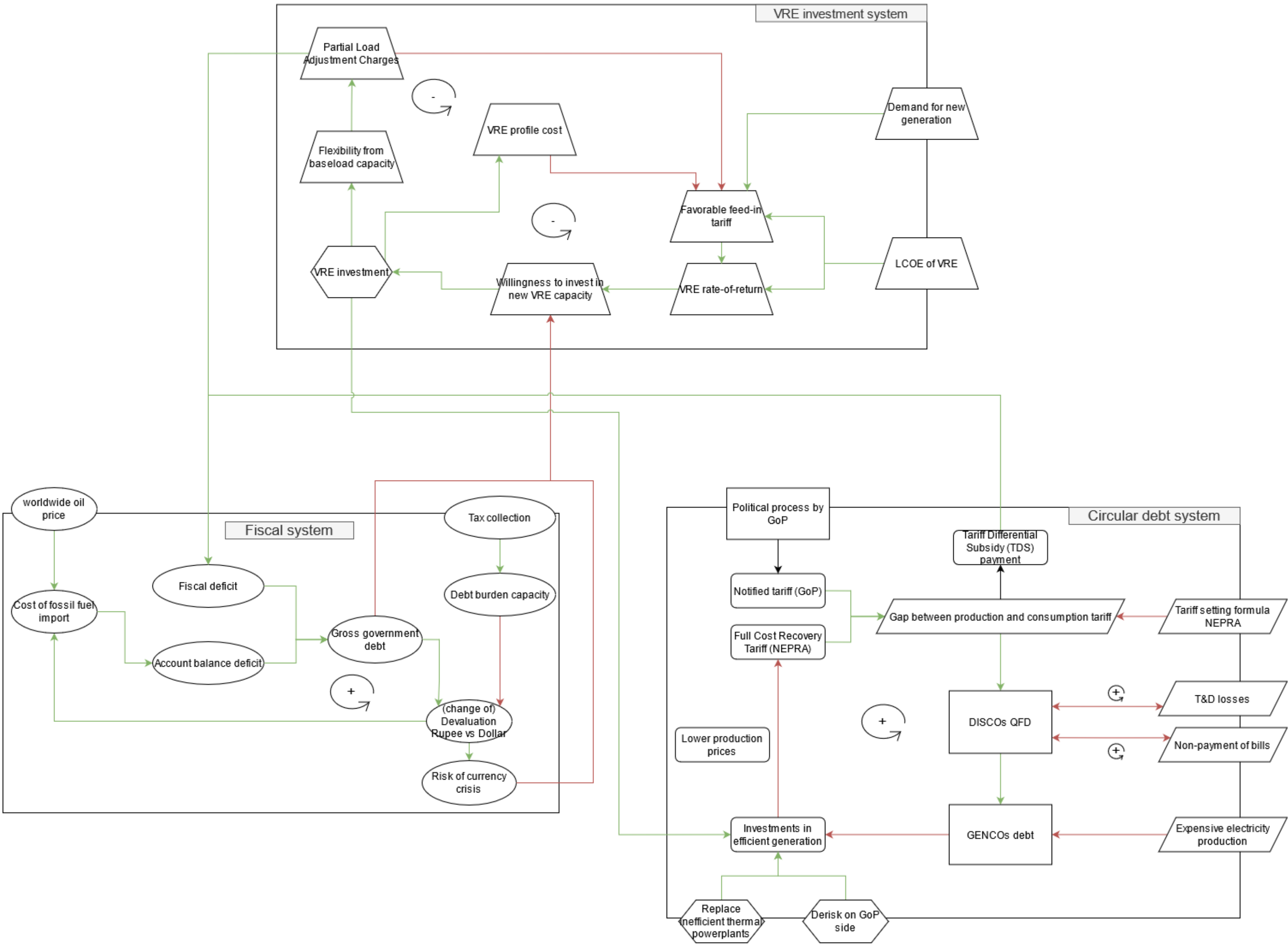

Figure 42: full causal relations diagram of circular debt system in Pakistan

The causal relations diagram is split into three interconnected systems: the fiscal system, circular debt system, and VRE investment system.

Taken as a whole, the conclusion can be drawn that the relationship between VRE investment and circular debt includes many intermediate factors. When adding up all the uncertain causal relations between the factors, erratic government policy, and unpredictable actor behaviour it is apparent that the system is too complex to capture in one agent-based model without losing tractability. Therefore, the system is demarcated to a fundamental abstraction level. This allow the model to still provide insight in the range of possible futures while preserving the necessary transparency, tractability, and reproducibility for the model to be useful (kraan et al. 2018). To this end, the conceptual approach is designed to include the minimum set of actors, behaviour rules and assumptions to explore the interaction between VRE investments and circular debt. Figure 2 shows the demarcated causal relations diagram for the purpose of the agent-based model.

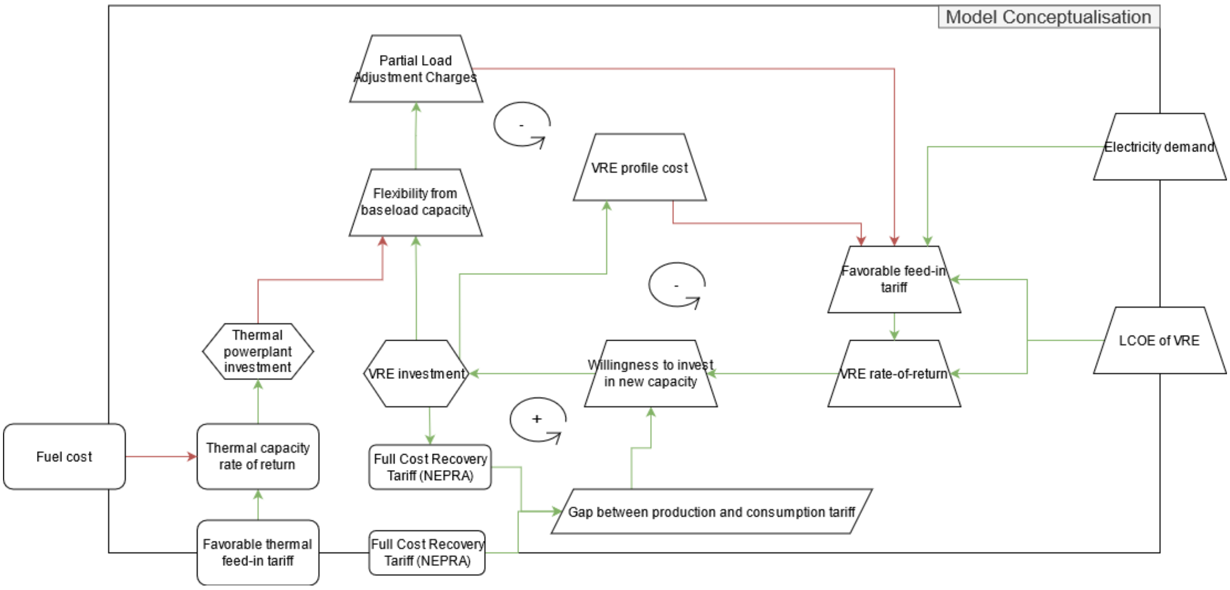

Figure 43: demarcated causal relations diagram

The inception point of the system is investment in either thermal or VRE capacity. Whether an investment is made depends on the willingness to invest and expected rate of return. When investments are made in VRE more flexibility is demanded from the existing baseload capacity due to the intermittent nature of the electricity production. Also, the profile cost increase with investment in VRE. When the Partial Load Adjustment Charges increase and the VRE profile cost increase the feed-in tariff for new VRE is expected to decline. This is because the GoP who determine the feed-in tariffs also carry the extra cost coming from PLAC and profile costs. Depending on the LCOE of VRE and the feed-in tariff determined by the GoP a rate of return can be calculated. The willingness to invest in new VRE capacity in Pakistan is determined by both the financial incentive and the risk coming from the circular debt accumulation.

The causal relation holds two negative feedback loops and one positive feedback loop. The two negative feedback loops are based on the extra costs resulting from a higher share of VRE. The positive feedback loop starts at an increasing share of VRE investments that reduce circular debt via a reduction in production prices. The reduced circular debt improves the willingness to invest by investors. The model will explore to which extent the positive and negative feedback loop influence the system performance.

Appendix C: Expert interviews

C.1 Guiding questions for interview

Agent: investor

What are the main drivers and barriers for an investor to invest in new generation capacity in Pakistan?

1. Determine the general set of factors that are considered by the investor agent prior to investment.
2. Try to probe towards an answer on the question why not all new generation capacity is VRE given its low generation cost measured in LCOE.

How do you decide in what kind of generation alternative you invest?

1. Determine the decision-making process for new investments by investors.
2. Split consideration into distinct decision points.
3. Specify the difference between investment in solar and wind.
4. Specify the difference between VRE and thermal investments.

What is the most important financial metric for investment decision? How is risk included in this metric? Are historical data used in this metric?

1. Get clarity on investors attribute regarding investment.
2. Determine the single most important risk measuring metric.
3. Determine the use of historical data in investment decisions
4. Try to elicit an answer on differences in risk appetite among investors.

What are the leading pieces of financial information from the market and CPPA necessary for an investor to decide on an investment?

1. Separate the information streams coming from the market and coming from the CPPA.
2. Determine information coming from CPPA
3. Determine information coming from market

Can you elaborate on the electricity price that (new) generation capacity receives? What is the most dominant type? Is their a difference between VRE and thermal energy prices?

1. Get clarity on the electricity price that is considered for a potential investment.

Agent: electricity market

Can you describe which production price (market price) you advise to considered when talking about the gap between production and consumer prices?

1. The questions aim to identify the market price that should be computed in the model. It could be based on the long term PPA tariffs or on OPEX + CAPEX cost of production facility.

How does the CPPA deal with an excessive production capacity?

1. Learn how it is decided which producer can produce in the single buyer structure of Pakistan.

Can you lead me through the working of the Partial Load Adjustment Charges (PLAC)?

1. What are the conditions of PLAC on tariff?
2. Does PLAC also apply to VRE?

Agent: Central Power Purchasing Authority

Can you explain how the CPPA determine the desired amount of installed capacity? What policy tools does the CPPA has to its deposal to reach this amount? Does the intermittency of renewable energy play a role in this consideration?

1. Learn what the considerations are of CPPA to allow new generation capacity.
2. Get a clear indication of the threshold CPPA has that indicate a stop or discouragement of new investments.
3. Identify whether the intermittency of renewable energy play a role in licence provision.

Currently, new generation capacity is allocated with an unsolicited tariff (benchmarking of cost). Allegedly, this system is going to change to a tender model. Can you talk me through both types and your expectation of this change?

1. Determine which tariff determination scheme will be used for the model

C.2. Summary interview 1

Senior investment officer Ton Nijensteen is specialised in renewable energy projects. Interview on 14th of April 2021. This interview was conducted in Dutch; therefore, the transcript is written in Dutch.

What is the most important financial metric for investment decision? How is risk included in this metric? Are historical data used in this metric?

Als je alleen een project hebt zonder financieringskosten (sponsor) dan gaat het erom dat investeringskosten terug verdient wordt in een bepaalde tijdsduur. Als je zegt dat zonnepanelen 20 jaar meegaan, dan betekent dit dat een investering van 100 miljoen binnen 20 jaar terug worden betaald. Dit is de basis.

Een stap verder is als het project wordt gefinancierd door banken die leningen verstrekken. Die leningen moeten worden terug betaald met bepaalde parameters (rate on return). Hoe dat eruit ziet, staat in het financiële model dat FMO maakt voor elke investering.

De volgende parameter is de productie van de panelen en de opbrengst per geproduceerde eenheid. Hoeveel een productie eenheid produceert reken je uit als door: geinstalleerde capaciteit * capacity factor .

De meeste zonnepanelen degraderen 0.5% per jaar qua productie.

Voor elk project in Pakistan levert de CPPA-G/Offtaker een cost-plus tarief aan. Dat is de prijs per geleverde MWh. Aan de hand van dit gereguleerde tarief wordt uitgerekend of het project voldoende winstgevend is zodat alle schuld terug betaald kan worden en dat alle andere investerings- en operationele kosten ook tijdig betaald worden.

Voor Sukkur is het rendement van de sponsors 9% in P50 en 7% in de P90 (P50 en P90 is uitgelegd in interview 1).

De belangrijkste factor voor omzet is de prijs die je krijgt per kWh tegen welk gereguleerde bedrag. De hoogte van de cost plus tarief (PPA) is daarom cruciaal.

De duur van de PPA tov de fysieke tijdsduur van het project is cruciaal. In bijvoorbeeld Oekraïne krijgt een project de eerste 10 jaar een feed-in cost plus tarief. Na die 10 jaar moet de geproduceerde elektriciteit worden verkocht op de spotmarket. De prijs op de spotmarkt is in het geval van Oekraïne 8x lager (dan het tarief onder de PPA) en volatiel/onzeker.

De risico’s die FMO meeneemt bij investeringen:

1. Landen risico (zoals wat er gebeurt in Myanmar)
2. Regulator risico en/of legal risico (bv. Blijft het PPA tarief gehandhaafd)
3. Resource risico (hoeveelheid zon, wind, water, etc.)

4. Construction risico
5. Operationele risico (kwaliteit van onderhoud & operations)
6. Unknown unknowns (sabotage, hacks, bliksem, aardbeving, overstromingen)
7. Environmental & social risk

Voor een investeerder is het belangrijk hoeveel van deze risico's verzekerd kan worden. Met een goed pakket verzekeringen kan een risicovol project alsnog worden gefinancierd.

De uiteindelijke rendement dat gevraagd wordt aan de hand van deze risico-analyse is gebaseerd op historische data (hetgeen andere al is overkomen), modellen en tacit knowledge van het bedrijf.

De rente die uiteindelijk gevraagd wordt op een project is niet alleen gebaseerd op risico. Het is geen uitkomst van een dynamisch stochastisch model van de risico's en marktinformatie. Er zit veel meer in, zoals o.a. gedrag en prijszetting door andere partijen, de toekomst verwachtingen mbt het land en/of de sector, etc.

In Pakistan wordt de spread op de lening vastgesteld door de overheid/Regulator op 4,25% (+ de base rate/US LIBOR). Meer dan dit bedrag wordt door de regulator niet meegenomen in het vaststellen van de PPA. Wat Pakistan hiermee effectief doet is investeerders en financiers onmogelijk maken om hun rente te koppelen aan het berekende risico van een individueel project. De verklaring om de marge te fixeren is dat de spread op de lening wordt meegenomen in de PPA tarief en als je het dan niet fixeert kan een investeerder hogere rente betalen wat een hoger PPA tarief oplevert en dus hogere kosten voor de consument.

Voor VRE is de cost-plus het all-inclusief bedrag. Voor thermische centrales is het cost plus bedrag plus de brandstof kosten (die veelal geïmporteerd worden en met fluctuerende, wereldmarkt prijzen).

De lokale politiek (Ministeries/Regulator/etc.) heeft veel invloed op welke PPA tarieven er worden uitgegeven.

Voor de wind investering in Sukkur is de return on equity van ca. 9% terwijl de investeerder Scatec >12% hanteert als minimum return on equity voor zulke projecten in Pakistan. Scatec neemt in feite een verlies dat ze niet kunnen compenseren door bijv. minder risico's te nemen. Het is dus een niet compenseerbaar verlies. Scatec investeert toch in Pakistan, omdat het desalniettemin past in hun strategie.

De investeringen in de elektriciteitsmarkt is een aaneenschakeling van zulke rationale en minder rationele beslissingen. Dit geld ook voor de overheid die zich laat beïnvloeden door non-financiële of risico gestuurde parameters die los staan van de financiële parameters van een investering. Dat maakt dergelijke investeringen in Pakistan in zekere zin "onvoorspelbaar".

Voor kolen verwacht ik een status-quo is. Er zal geen drastische vermindering in kolen zijn in Pakistan en zeker niet in absolute termen. Hooguit vermindert het verhoudingsgewijs in de toekomst.

Can you describe which production price (market price) you advise to considered when talking about the gap between production and consumer prices?

De Short Run Marginal Cost zijn niet gelijk aan de PPA tarieven voor elektriciteit. Operationele kosten voor wind en zon zijn het laagste in vergelijking met thermische centrales. Voor zon en wind is de investering wel weer heel hoog. In de Wereld Bank modellen waar wordt gerekend met SRMC, wordt het investeringscomponent volledig aan.

Let op dat je in Europa ook lange termijn contracten hebt tussen grote afnemers en producenten. Dat gaat niet op marginale kosten maar op de investeringskosten plus de OPEX, marge en rente.

Hou dus in de gaten dat een markt niet kan functioneren op een fluctuerende dagprijs.

De KPI markt prijs heet de contracted market price dat de prijs is voortkomend uit de PPA tarieven van de centrales. Zowel voor productie als idle capacity.

Een centrale krijgt betaald voor curtailment zodra curtailment niet-excuseerbaar is. Hoe de vergoeding in Pakistan wordt geregeld is onderhandelbaar. Soms is dat een deel van de PPA tarief, soms is dat de dagprijs.

I.h.a. geldt dat Curtailment gedurende een aantal dagen per jaar niet wordt gecompenseerd door de Offtaker: boven deze drempel, wordt pas e.e.a. vergoed.

Can you explain how the CPPA determines the desired amount of installed capacity? What policy tools does the CPPA has to its deposal to reach this amount? Does the intermittency of renewable energy play a role in this consideration?

Ten eerste kan het probleem van fluctuatie op het net worden verbeterd door IT integratie. De vraagkant van Pakistan is redelijk voorspelbaar. Pieken zijn er 's ochtends en 's avonds. In Pakistan is er ook tijdens het middag uur een piek vanwege airco.

Er moet ongeveer 5% overcapaciteit zijn die snel kan op en afschakelen (gas centrales). Er is geen spotmarket in Pakistan want alle contracten worden afgesloten met de overheid. Het is niet mogelijk om een contract af te sluiten tussen private actoren.

Zon, wind en hydro worden altijd afgenomen door de Offtaker ("priority dispatch convention"). De thermische centrales kunnen wel worden afgeschaald. Wat er blijft staan zijn de (vaste en sommige variabele) kosten voor O&M.
In de PPA met een thermische centrale werkt het als volgt: de centrale krijgt een vast bedrag elk jaar voor O&M en daarnaast een bedrag voor elk geleverde kWh. De CAPEX wordt terugverdiend uit hoofde van beide posten. In de O&M kosten zit de debt service in de kWh prijs zit naast de fuel price ook een vergoeding waarin winst gemaakt kan worden. De 'partial load adjustment charges' ontvang je als je minder produceert dat de ondergrens afgesproken in de PPA.

De PPA wordt zo gekozen door de CPPA-G dat een investeerder precies uit de kosten komt aan de hand van de huidige markt kosten. Als er geen harde noodzaak is voor nieuwe capaciteit in de komende 3-5 jaar dan gebeurt dat gewoon niet. De CPPA doet dan gewoon de PPA tarieven sterk naar beneden.

C.3. Summary interview 2

Investment officer and credit officer Sander Daniels at FMO. Sander Daniels assessed renewable energy investment option in Pakistan. Interview on 15th of April 2021. This interview was conducted in Dutch; therefore, the transcript is written in Dutch.

How does the CPPA calculate the feed-in tariffs for new generation capacity?

How does the process go to get a feed-in tariff of NEPRA?

FMO is niet betrokken bij het verkrijgen van een feed-in tariff. Dat is de taak van een project ontwikkelaar. Als FMO instapt heeft de ontwikkelaar al de benodigde vergunningen verkregen en een PPA tariff. Op een gegeven moment wordt de project ontwikkelaar geschikt geacht om een tarief verzoek in te dienen bij NEPRA. In een tarief verzoek geeft de project ontwikkelaar aan: welk type capaciteit, op welke locatie, met welke technologie, welke bouwer ze verwachten, welke financier ze verwachten, welke kosten ze verwachten. Kortom, de project ontwikkelaar geeft een schets van hoe het hele project eruit gaat zien. Uit deze schets komt na een review van NEPRA een voorlopig oordeel van NEPRA welke kosten gegrond worden bestempeld en dus mogen worden uitgegeven onder het 'cost-plus' tarief. De 'plus' gedeelte van de 'cost-plus' is een door NEPRA bepaalde hoeveelheid return-on-equity dat de ontwikkelaar verdient. Hieruit komt een cost-plus tariff (in thesis de PPA tariff) dat een kWh prijs is waarin de kosten (OPEX + CAPEX) en de return-on-equity (winst) wordt verdient.

Dit is duidelijk anders dan het tender model (zoals in Europa) waarin de project ontwikkelaar met de laagste kWh prijs het project mag bouwen ongeacht hoe de invulling is van de financiële posten.

In de cost-plus systeem zit NEPRA dichter op het project dan bij een tender systeem.

Voorbeeld posten verdeling in een cost-plus contract. De volgende posten worden opgenomen:

- EPC (engineering, procurement, construction)
- Financierings kosten
- Return-on-equity

Al deze posten krijgen een specifiek bedrag van NEPRA dat een projectontwikkelaar maximaal mag toeschrijven op een post. Wanneer er kosten overschrijding is op een post en een besparing op de andere kan dat elkaar niet compenseren. Een projectontwikkelaar moet de overschrijding zelf betalen en de besparing worden gedeeld tussen NEPRA (60%) en de projectontwikkelaar (40%). NEPRA houdt nauwlettend alle kostenposten in de gaten.

Return-on-equity wordt vastgesteld rondom 14% door NEPRA maar veel projecten komen duurder uit (boven de maximum van de toelaatbare kosten) en hebben daardoor een werkelijk ROE rond 9%.

How are the executable values for each financial term determined by NEPRA?

Ze gebruiken benchmarking data met andere landen en historische data.

Een van de indicatoren die NEPRA meeneemt is de rente over de lening van de projectontwikkelaars. Eerder was dit LIBOR + 4.5%, soms zijn financier bereidt om dan 4.25% aan te bieden zodat de ontwikkelaar 40% kan verdienen op het verschil. Toen die 4.25% werd geboden heeft NEPRA vervolgens de maximum rente verlaagd naar 4.25%.

How does the CPPA deal with an excessive production capacity?

Zon-en-wind projecten zijn take-or-pay contracten waarin staat dat de CPPA verplicht is om te betalen voor alle stroom die geleverd is of had kunnen worden geleverd. Omdat duurzame energie geen brandstof gebruikt is het logisch om die altijd te laten draaien. Bij fossiele centrales als je die uitzet hoef je namelijk geen brandstof te betalen alleen de winst die gemaakt had kunnen worden.

Een complicerende factor zijn koopcontracten met buitenlandse brandstof leverancier. In de koopcontracten staat een afnameverplichting. Dus soms moeten er misschien marginaal duurdere fossiele centrales draaien om ervoor te zorgen dat er aan de koopcontracten wordt voldaan. Pakistan heeft contracten met andere landen voor de levering en verplichte afname van olie of gas.

Er is heel veel debat geweest over hoe de berekening voor compensatie van niet afgenomen stroom precies toegepast werd door NEPRA. Er is uiteindelijk veel ambiguïteit in zulke contracten.

Dit zijn complexe en politieke processen en stijgt daardoor boven een rekensom uit.

Can you explain how the CPPA determines the desired amount of installed capacity? What policy tools does the CPPA has to its deposal to reach this amount? Does the intermittency of renewable energy play a role in this consideration?

Dit is mij niet helemaal duidelijk. Al wordt het PPA tarief niet als enige middel ingezet om project ontwikkelaar te verleiden tot een investering. Voor ontwikkelaar is het ook belangrijk hoe stabiel zijn de wetten en het beleid dat gevoerd wordt. In Pakistan komt het voor dat er een beslissing wordt gemaakt voor een bepaald tarief en dat een nieuwe regering zo’n beslissing gaat heroverwegen wat dan weer een jaar kost. Een project ontwikkelaar moet al aanzienlijke kosten maken voordat ze beginnen met bouwen van de powerplant. De hoogte van die voor-investering en het risico of het leidt tot daadwerkelijke bouw is belangrijk voor project ontwikkelaars. Hierin is de hoogte van de PPA een onderdeel maar niet cruciaal.

De cost-plus tariff wordt gecompenseerd voor inflatie en de exchange rate tussen US$ en PKR. **Waarom is de voornaamste investering niet in VRE als die tarieven lager zijn dan fossiele alternatieve?**

Dat is een vraag die ik moeilijk kan beantwoorden. Het zou iets te maken kunnen hebben met de zwakke transmissie systeem dat volledig is ingericht op conventionele energie. Een systeem is gewend van oudsher om op een bepaalde manier te werken. Er zijn belangen in hoe het altijd werkte, niet in de slechte zin van het woord, en dat zorgt ervoor dat een bepaalde weg belopen blijft.

Daarbij kan het ook zijn dat de voordelen lager worden ingeschat en de nadelen hoger worden ingeschat voor duurzame energie door de overheid (bij maken van beleid, red.) en NEPRA (bij opstellen van PPA, red.).

Er zijn ambities voor 2030 voor duurzame elektriciteit. De vraag is waarom worden die dan niet gehaald. Een voorbeeld hierbij is dat VRE projecten in de aanloop naar de bouw regelmatig stil komt te liggen door vertragingen van de kant van de overheid. Dit is voor project ontwikkelaars onprettig en financieel negatief. Soms stappen investeerder of project ontwikkelaars dan uit het project voordat het materialiseert. Deze vertragingen in het proces vermindert het aantal investeringen.

C.4. Summary interview 3

Renewable energy project finance specialist Mark Roesink made several investments in renewable energy projects in Pakistan. Mark Roesink is currently investment officer at FMO. Interview on 13th of April 2021.

Demarcation (no formal question)

Storage is a technology that became 80% cheaper in the past years. Therefore, it will become a major player and influencer of the energy transition. The main effect of the introduction of storage is worse business case for gas powered plants, especially for countries who have no domestic gas resources.

What are the main drivers and barriers for an investor to invest in new generation capacity in Pakistan?

FMO imposed a fossil fuel investment ban on thermal power plants in all countries except for the least developed countries[13]. Pakistan is not a least developed countries and therefore FMO does not invest in fossil fuel generation capacity. An important barrier to decide on an investment is the expectation of the future fuel prices. Based on the projected fuel price NEPRA provide a PPA tariff that reflects the willingness to invest in a particular generation capacity. If the expectation is a relatively low fuel price the business case of fossil powerplant is made more interesting by providing better PPA conditions. In the end the goal of NEPRA is to have the lowest electricity price.

There are other banks that do invest in fossil fuel powerplants, but they also look at the long-term business case of those investments. For the bank, the risk is a non-payment when fuel prices increase too much (an investor is covered for fuel price fluctuation through a cost-plus clause in the PPA). If the fuel price rise by a lot, the utilities are not able to pay the extra cost. This makes the government responsible. For investors, the question is whether the government is able to pay these rising subsidy cost.

[13] The least developed countries is defined by the United Nations Conference on Trade and Development

Investment barriers

The market price or PPA tariff is not equal to the CAPEX + OPEX because project developers and financier do need to make a profit. For each investment the PPA tariff is crucial for the investor. There are different types of PPA's:

- cost-plus tariff (currently used in Pakistan)
- negotiable tariff
- feed-in tariff also known as fixed price
- floating tariff (not applied in Pakistan)

In the case of a cost-plus PPA NEPRA permits a certain expenditure on the CAPEX and OPEX plus a profit margin of approximate 11 -13%. The profit margin is negotiable. The cost plus PPA price can also be determined based on bi-lateral, confidential negotiations. In this case the rationale behind the PPA tariff remains unknown.

Probably Pakistan will switch in the near future to a tendering process for renewable energy investments.

Country risk classification

Banks have an internal list of the risk classifications per country. The classification is based on data from a.o. credit rating agencies. The risk classification determines the internal rate of return deemed necessary for an investment. In general countries with higher risk levels have to pay higher PPA tariffs or the tender tariffs are awarded to higher bids.

What is the most important financial metric for investment decision? How is risk included in this metric? Are historical data used in this metric?

The first is whatever somebody is willing to offer. Sometimes an investor is willing to go below cost price to enter a market and then later increase their price for a larger project.

For project developers in general the exact calculation of an investment comes with different metrics being combined and interpreted by their board of directors. Furthermore, some projects just happen as they were based upon bi-lateral and private negotiations between the project developer and the government. A project developer will lose its negotiation position if the government knows the room to negotiate of the project developer. In the end the decision and information come together within a small group inside the company.

For an outsider it is impossible to know the acceptable cost of project developers in a cost-plus market. It is possible to estimate the cost by searching the cost of transformers, solar panels, wind turbines, other equipment, transport cost, insurance, efficiency, solar irradiance, maintenance.

For the electricity revenues, financiers, investors, and project developers calculate a P50 and P90 scenario. This is the change that the electricity yield is higher than the 10-year expected average yield. P90 is more conservative than P50. Project developers look at P50: banks are more conservative and look at P90.

In summary, the investment cost (CAPEX) and lifetime operational cost (OPEX) are calculated within a bandwidth. Then the revenue is calculated on the PPA price times the expected electricity yield. The electricity yield is based the P50 and/or P90 scenario. Then a profit margin is included based on the project risk and internal profit expectations.

An expectation of the cost-side is the levelized cost of electricity. It should be specified to Pakistan.

On which metric are differences between investors?

Expectation of the loss giving default. For a lender also the expectation of the quality of the project developer and the technology that is used. Furthermore, the expectation of the professionality of instalment and management of the asset. All these metrics are estimated differently by different investors.

How does the CPPA deal with an excessive production capacity?

PPA contract include an agreement on the yearly produced electricity. If more electricity is produced, the CPPA only uses this electricity if there is capacity needed on the grid. The tariff that the project developer receives for the excess electricity can differ from the PPA tariff.

Which power plants produce goes according to the merit order. The CPPA sometimes curtails powerplants if the PPA price is higher than other available production capacity. Sometimes the CPPA does not compensate for the availability of a powerplant.

What happens when the security of supply decreases due to variability of renewable energy?

The CPPA is not in this situation and therefore there is no policy on this matter. However, when looking at other countries something should be done in such a situation with capacity payments or reserve capacity.

C.5. Summary interview 4

Interview with international investment expert working in and from Pakistan. Interview on 17th of June 2021.

Guiding questions for the interview

- How do Investors decide in what kind of generation alternative they invest?
- What is the most important financial metric for their investment decisions? How is risk included in this metric?
- How is the PPA tariff for a new powerplant negotiated? How much does NEPRA dictate, and what are the means for an investor to reach an acceptable/favourable price?
- Why is there a large difference in PPA price for coal (~70 US$/MWh) compared to solar (~32 US$/MWh)?
- Which and what are possible/desired policy interventions to be taken by the government which can [further than under current policies] stimulate Renewable and in particular solar and wind energy?
- To which extent will [more of such] solar and wind investments influence (or not) the Circular Debt situation going forward?

How do Investors decide in what kind of generation alternative they invest?

RE is a relative new generation alternative (first wind project reached COD in 2013, 2010 started the initial works for this project). It is important to understand that during the first solar and wind projects there were severe electricity shortages with load shedding consequently.

The decision to start with RE came from the government top with the rationale that in India wind energy was a major resource. That first wind project was a success and is replicated after that. Even though solar is a widespread resource, it was not used at that time. A factor that kept new RE projects from realisation was a strong lobby from interest groups that believed in another (thermal) energy strategy.

There are two types of solar projects: government projects and private projects. The first project (first solar project COD 2016) was performed the government to create a success story and decrease the power shortage.

It is not about alternatives, but it is about what is made available and what has a success story behind it. Also, where is a good return on investment to be made. There is not much choice in the matter of investment alternatives.

The government identified in the past 10 years where the RE resources are located. If you want to do a project you go to all relevant government entities to ask where RE projects could be developed. Besides business cases with irradiance or windspeed also the local or regional security situation and the competence of the local government are relevant.

In 2006 the first RE policy was introduced by the government. Then it took four years to start the first wind project which reached COD in 2013. The framework to issue LOI for new private projects were available from 2006. The RE 2006 policy also included the steps that a project developer should take before a final PPA is issued by NEPRA.

There have been three different tariff regimes applied in Pakistan (period is unclear): first feed-in tariff (FIT). This gave a clear insight for a project developer in their expected earnings. Thereafter came the cost-plus tariff. Cost-plus tariff is not a negotiation. NEPRA accepts some cost and some cost are not accepted and that is what you should work with as project developer.
The government now want to go to competitive bidding/tenders.
3 tariff regimes: (1) FIT -> good returns and lot of security for investors (2) cost-plus (not really a negotiation, you come with a business case and the government accept some cost and some not) (3) now NEPRA tries to go to competitive bidding.

- ➢ What is the most important financial metric for their investment decisions? How is risk included in this metric?

For a project developer the process to invest is very pragmatic. When a decision is made to pursue a project or market they continue and have the stamina to pull trough. First investment gateway is to enter a country: macro industrial risk and opportunities and the pipeline of other similar projects. They scan the market for the potential to grow in a country with similar projects. Also, they look at the share the project developer could take now and in the future. A project developer needs a pipeline of more projects to make economic sense to invest in a new country. The initial analyses were not very elaborate due to limited capacity of the company. Investment decisions were also made due to the guts feeling of senior management. Now the decision making is more structured because the project developer grew by a lot. Second gateway is that the development budget is approved by the company to go through the initial stages.

Cost-plus tariff is more complicated to model. All the decisions the project developer makes on cost has an influence on the tariff which makes it very complicated to construct a reliable proposal. Cost-plus decision was solely made by Nepra. They tried to lobby and nudge but Nepra made the decision to which the project developer had to accept. The proposition was rock bottom, EPC was very low. To manage to pull through on this proposition is very challenging. And the returns are not very high.

- ➢ Why is there a large difference in PPA price for coal (~70 US$/MWh) compared to solar (~32 US$/MWh)?

The various regulatory entities are believed to be politically driven. It is quite decentralised. So lot of decisions are made over a large number of platforms. Nepra is navigating between low electricity prices and energy security.

Nepra perspective -> in first 5 projects, they took a big risk with resource risk. This is the biggest risk of all. After that these 5 projects, the risk is allocated to investor.

The tariff is not a one-way-street. There are multiple factors determining the decision for PPA price by NEPRA:

- What is the government saving? If the government adopt this project they think what am I saving compared to the portfolio?
- How much capacity is available? Now it is excessive, this reshuffles the tariff decision. The government still has to pay the capacity payment part of the PPA if there is excessive electricity. This makes new PPA difficult to attain compared to 10 years ago.
- International benchmark of other RE projects. This influences the decision making. Of course, you cannot compare 1 on 1 but it put pressure on the government. Newspaper

writes about it if Pakistan buys for 5 cent and in India it is 2 cents. This put huge pressure on the government and NEPRA.

- Price of the equipment is going down. NEPRA can't accept higher cost in their cost-plus contract because of this. If higher costs are provided NEPRA will receive lots of questions.
- Circular debt issue. Government experimented with capacity payment which resulted in circular debt. This circular debt forces the government to go as low as possible with new technologies.

NEPRA learns from previous occurrences. With for example high thermal investments, also pegging to US$.

The coal investments are done because there are domestic coal mines developed. The expectation by the government is that once the mines are developed the cost will drop.

➢ To which extent will [more of such] solar and wind investments influence (or not) the Circular Debt situation going forward?

Negative: CD has multiple reasons. Large reason for CD is due to capacity payments for thermal plants. RE always produce when there is sun or wind and then fossil powerplants stand still but government still has to pay these capacity payments. Therefore, RE electricity is cheap but at the same time capacity payments rise because thermal powerplants are pushed out of the merit order.

Positive: If energy prices are higher than CD will be higher and vice versa. Because RE allows lower energy generation this will reduce CD.

Appendix D: Assumptions

ASSUMPTIONS ABOUT INVESTORS		
Assumptions	**Topic**	**Explanation**
A1	Generation alternatives	Investors choice for new generation capacity is limited to coal, gas, wind or solar.
A2	NPV calculation	The calculation of the Net Present Value (NPV) is based only on OPEX and CAPEX. This means no taxes, finance cost, interest, depreciation or amortization is included.
A3	NPV calculation	All NPV values are normalized towards a 1000 MW investment. This means that the NPV value of gas is multiplied by two, because the asset capacity is 500 MW. This is necessary to achieve an interval scale with the right difference between the NPV's
A4	Construction of new powerplant	Every investment in new generation capacity equals an investment of 1000MW. Therefore, investment in a 500 MW gas fired powerplant is performed twice. The same holds for wind and solar facilities.
A5	Power Purchase Agreement	New generation capacity receives a fixed cost-plus PPA tariff for the lifetime of the asset.
A6	New entrants	There are three types of investors without the possibility of new entrants
A7	Construction time	No construction time is included in the model
A8	Profile cost	Profile costs for VRE are incorporated as fuel costs in the NPV calculation

ASSUMPTIONS ABOUT NEPRA		
Assumptions	**Topic**	**Explanation**
B1	Capacity payments	The effect of capacity payments is not included in the model. Only the cost for electricity production is assessed. One of the effects is that the high public cost for heavy fuel oil is just partly included in the model results.
B2	New generation capacity	Every year the maximum allowed new generation capacity equals the gap between the generation capacity at the end of the previous year and the electricity demand set by NEPRA.
B3	PPA tariff decline	Overtime the PPA tariffs of all generation types decrease with a uniform percentage
B4	Profile Cost	The profile costs are not included in the PPA tariff, but costs are passed on to consumers. This is in line with the common practice in OECD countries that profile cost are socialized over all consumers.
B5	Demand	The demand at model initialization is set equal to the produced electricity. This is done to prevent the model to make a large number of investments in the first year to compensate for the lack of production capacity. Currently, there are no severe power shortages in Pakistan therefore this assumption is viable (NEPRA, 2020).

ASSUMPTIONS ABOUT ELECTRICITY MARKET		
Assumptions	**Topic**	**Explanation**
C1	Market segment exclusion	K-electric is excluded in the model. This is due to its small installed capacity compared to the national grid. Also, the market dynamic because of the privately owned characteristic differs from the national grid which add extra complexity.
C2	Generation type phase-out	Heavy Fuel Oil (HFO) is slowly phased out.
C3	Generation type phase-out	Due to restrictions in generation type investments the share of biofuels, nuclear and hydro slowly phase-out
C4	Electricity import	The model does not consider electricity import or outport
C5	Initial assets	The older the powerplant the lower the efficiency and therefore the LCOE (Cui et al., 2019; European Environment Agency., 2015; NEPRA 2020, 17)
C6	Storage	No storage solutions are available
C7	Fuel cost variability	Fuel cost are kept stable throughout the model. In reality fuel cost can fluctuate sharply.
C8	Grid capacity	All produced electricity, including variable renewable electricity, is always accepted on the grid
C9	Electricity demand	Electricity has a constant growth factor.

ASSUMPTIONS ABOUT GENERATION ASSETS		
Assumptions	**Topic**	**Explanation**
D1	Production capacity	Generation capacity [MW] of an asset is expressed in gross capacity. Gross capacity is the total electricity generated by the generator. Some of this electricity is used onsite to power the facility. The net capacity is the generated electricity that leaves the premisses. In the case of the coal powerplant of the China Power Hub Company the gross capacity is 660 MW, and the net capacity is 607 MW.
D2	OPEX calculation	The operational expenditure consists out of fuel cost. No variable or fixed operation and maintenance (O&M) is considered. For FMO financed Sukkur solar project the lifetime OPEX consist out of (undiscounted) 26% of total revenue.
D3	Cost reduction or efficiency increase for thermal powerplants	For Coal and Gas powerplants it is assumed that their overall performance remains equal to the initial performance. This means that the LCOE remains flat besides fluctuations in energy price. This is in line with expectation provided by NREL (2020).
D4	Learning effect and technology development VRE	New wind and solar assets have a lower CAPEX when they are built further in the future. The capacity factor does not increase over time.
D5	Property gas assets	All gas fired powerplants are assumed to be Combined Cycle Gas Turbines (CCGT). CCGT equals 32% out of total 33% electricity produced by gas fired powerplants (NEPRA, 2020).
D6	Profile cost VRE	The levelized cost of electricity for new VRE assets increase above a threshold value of VRE in the energy mix. Parameterization according to Heptonstall and Gross (2021)
D7	Profile cost VRE	The profile cost for wind and solar electricity is equal. This is in contrast with the expectation that profile cost for solar is higher than wind because the firm capacity of solar plants is lower than wind plants.
D8	Capacity factor wind	The capacity factor of wind is the average between FMO's capacity factor and the calculated actual CF. FMO's capacity

		factor is rather high but as observed in OECD countries over time the sweet spots are occupied and turbines are placed on lower CF spots. The reason for the low calculated CF remains unclear but it is at the lower level of the spectrum described in the literature.
D9	Oil (HFO) LCOE	LCOE of heavy fuel oil is set on 200 US$/MWh. This is based on the interpretation from data received from ACWA Power (2017) and Mayr (2014). This data is not specific for Pakistan's HFO installations. Therefore, the real data could vary.

OTHER ASSUMPTIONS		
Assumptions	**Topic**	**Explanation**
E1	Inflation	Monetary values are not inflation corrected
B2	Exchange rate	All values are reported in US Dollars and no exchange rate variability is included

Appendix E: Initial installed capacity input variables & benchmark

At initialisation of the agent-based model Pakistan's currently installed generators are included as assets in the electricity market. See Table 13 for an overview.

Table 13: Overview of the installed capacity broken down into generation type. Also, the per asset capacity for powerplants in the agent-based model is presented. The third column present the lifetime of an asset. The fourth column shows the capacity factor of the generation asset. The last column shows the amount of initially installed assets, the numbers are rounded to the nearest multitude of the respective asset capacity. Source: NEPRA 2020, 94, World Bank 2020b 24, 56,83, FMO sukkur investment

Generation type	Total installed Capacity [MW]	Lifetime	Per asset capacity	# Model initial assets (rounded)
Hydro	9,861	50	1000 MW	10
Nuclear	1,467	50 (40-60)	1330 MW	1
Coal	5000	34 (28-40)	1000 MW	5
Gas (CCGT)	11784	30	500 MW	24
Oil (HFO)	5714	30	1000 MW	6
Wind	1,248	25	400 MW	3
Solar	430	25	400 MW	1
Bagasse/ Biomass	369	30	200 MW	2
Total	**36672**			

Information on installed capacity provided by NEPRA (2020) represent thermal energy as a single source. To break this down into gas, oil, and coal the respective shares of the generation types in the total generation capacity is used from The World Bank (2020, 83). In total 63% of the generation capacity in 2019 was thermal (fossil). The respective shares for Gas (CCGT), Oil, and Coal were 33%, 14% and 16%.

Electricity generation

Information on installed capacity does not provide information on how much time certain powerplants produce electricity. The actual produced energy in MWh is a crucial metric for calculation about the energy price. The electricity generation is calculated as follows:

(1) Electricity generation [MWh/year] = Installed capacity [MW] * Capacity factor * 8760

The capacity factor is the actual electricity out output over a given period to the maximum possible electrical energy output over the same period. The 8760 represent the number of hours in a year.

The electricity generated and associated capacity factor is presented in Table 14.

Table 14: Electricity generation in MWh per generation type and capacity factor. Source: electricity generation by type NEPRA 2020, 98 and NEPRA 2020, 117.

Generation type	Electricity generation (MWh)	Average capacity factor
Hydro	38,987,960	45%
Nuclear	9,897,890	85%
Gas	15,236,300	37.8%
RLNG (Gas)	23,830,580	37.8%
RFO (Oil)	4,178,250	8.3%
Coal	25,553,340	57.3%
Wind	2,882,480	35%[14]
Solar	704,970	18.7%

[14] For Wind energy the calculated CF is ignored because of the large difference with benchmarking numbers. Therefore, a average between the calculated CF and FMO's CF is used which equals 35%. Refer to assumption D8 for more information.

Bagasse/Biomass	564,460	17.5%
Total	121,836,910	

Capacity factor calculation

The capacity factor is an important input variable in the Net Present Value (NPV) calculation. Data sources provide information on the electricity generation [MWh] and on the installed capacity [MW]. With this information the capacity factor can be calculated using the following formula:

(1) Capacity factor = electricity generation [GWH] / (total installed capacity * 8760)

Capacity factor data comparison

The calculated capacity factors as mentioned above is based on a snapshot of one year worth of production and installed capacity. To put the numbers into perspective a comparison of capacity factors among different sources is made and presented in Table 15.

Table 15: Capacity factor of generation alternatives. Retrieved from 4 different sources.

Generation type	Calculated average actual CF	CF World Bank data	CF National Renewable Energy Laboratory data (average)	FMO CF
Hydro	45%	49%[15]	62 – 66 %[16]	-
Nuclear	85%	67%%[17]	93%	-
Coal	57.3%	49.4%[18]	54%	-
Gas (CCGT)	37.8%	48%[19]	55%	-
Oil (HFO)	8.3%	No data	No data	-
Wind	26,4%	25 – 45%[20]	38 – 41%[21]	43.6%[22]
Solar	18.7%	17.5%[23]	22 – 35%[24]	17.8%[25]
Bagasse/ Biomass	17.5%	49%[26]	61%	-

Consumption versus production
An interesting point to note is the gap between energy production and energy consumption. For 2019/20 the energy consumption was 97,793,750 MWh (NEPRA 2020, 177) while the energy production was 121,836,910 MWh.

[15] Retrieved from World Bank 2020b 24
[16] Data based on 8 data points located outside Pakistan. CF of hydropower is very site specific
[17] Retrieved from World Bank 2020b 24
[18] Retrieved from World Bank 2020b 24
[19] Retrieved from World Bank 2020b 24
[20] Retrieved from World Bank 2020b 41
[21] The CF of wind depends strongly on the average windspeed. Range between 16% to 52%. Depicted data is based on the average windspeed of the Lakeside project
[22] Based on Lakeside project.
[23] Retrieved from World Bank 2020b 56.
[24] Data is based on 5 utility PV projects located in the USA.
[25] Based on Sukkur solar PV project
[26] Retrieved from World Bank 2020b 96

Appendix F: Net Present Value input variables & benchmark

The Net Present Value is calculated using four components (1) Capital expenditure, (2) operational expenditure (assumed: only fuel cost), (3) the cost-plus PPA tariff provided by NEPRA, and (4) the discount value. Data on the first three components is presented in this appendix.

Table 16: Overview of NPV input data

Generation type	CAPEX [US$/MW]	Fuel cost [US$/MWh]	PPA tariff [US$/MWh]
Coal	1,448,636	35.54	67.57
Gas	872,000	38.75	88.41
Wind	1,309,600	-	47.00
Solar	695,333	-	32.31

F.1. PPA tariff

The PPA tariff consist of the following components according to NEPRA (2020):

A. Energy Purchase Price
   a. Fuel Cost Component
   b. Variable O&M Local
   c. Other cost
B. Capacity Purchase Price
   a. Fixed O&M (Local)
   b. Fixed O&M (Foreign)
   c. Insurance cost
   d. Cost of working capital
   e. Return on equity
   f. Debt service (Principle Repayment and Interest Charges)

As model input parameter, whenever possible, the levelized PPA tariff over the lifetime of the asset with a 10% discount factor is considered.

Coal. As reference case for the PPA tariff of coal the China Power Hub Generation Company 2016 PPA application is selected. The application concerns a 2 x 660 MW coal powerplant. According to the 2016 upfront approval of NEPRA the levelized PPA tariff is determined at 67.57 US$/MWh.

Gas. As reference case for the PPA tariff of Gas the Kolachi Portgen Limited 2019 PPA application is selected. This concerns a 450 MW RLNG based Combined Cycle Power Plant. The determined PPA tariff is 88.41 US$/MWh. This is the PPA tariffs if the powerplant is producing 100% on Regasified Liquefied Natural Gas (RLNG). The powerplant can also generate on heavy fuel diesel (HFD) with a higher PPA tariff.

Wind. As reference case for the PPA of Wind energy the 50 MWp Lakeside wind energy project is selected. This is a FMO co-financed project that is expected to start producing electricity in 2021. The 2019 NEPRA approved levelized PPA tariff is 47 US$/MWh.

To compare: two projects (Metro, Gul Ahmed) finished in 2015 received a PPA tariff of 150 US$/MWh. A 2017 wind project (Zephyr) received a PPA tariff of 100 US$/MWh.

Solar. As reference case for the PPA of Solar energy the 150 MWp Sukkur solar plant is selected. This is a FMO co-financed project for which approval is provided in 2021 and construction is expected to finish in 2022. The levelized tariff at 7% discount rate is 32.31 US$/MWh.

To compare: Gharo solar power which is also a FMO financed 50 MWp solar energy project that started generation in 2019 received a PPA tariff of 56 US$/MWh.

F.2. Capital expenditure (CAPEX)
The CAPEX of a project encompasses the initial investment of a new production asset.

Coal. As reference case for the capital expenditure of coal the 2016 PPA application by the China Power Hub Generation Company is considered. The application concerns a 2x 660 MW coal powerplant. The project cost for 660 MW is assumed to be: 956.1 Million US$. This includes besides the 767.0 Million US$ capital cost also the finance charges, taxes, and fees. Therefore, the capital expenditure per MW is assumed to be: 1,448,636 US$/MW.

To compare: the 2020 National Renewable Energy Laboratory data reports a CAPEX of 4,150,000 US$/MW for a coal powerplant with an average capacity factor.

Gas. As reference case for the PPA tariff of Gas the Kolachi Portgen Limited 2019 PPA application is selected. This concerns a 450 MW RLNG based Combined Cycle Power Plant. The proposed project cost by Kolarchi Portgen Limited totalled 392.4 Million US$. Of this amount 345.1 Million US$ is concerned with constructions. The remainder is spent on Financial fees & charges, interest during construction and ECA Premium. This brings the CAPEX on 872,000 US$/MW.

To compare: the 2020 National Renewable Energy Laboratory data reports a CAPEX of 983,000 US$/MW for a gas powered powerplant on average capacity factor.

Wind. As reference case for the PPA of Wind energy the 50 MWp Lakeside wind energy project is selected. This is a FMO co-financed project that is expected to start producing electricity in 2021. The NEPRA approved project cost totals 65.48 Million US$. These costs encompass besides construction costs also taxes, insurance, and finance fees. This brings the CAPEX on 1,309,600 US$/MW.

To illustrate the decline in CAPEX over the past years: Gul ahmed (2015) 2,6 Million US$/MW and Zephyr (2017) 2.3 million US$/MW.

To compare: the 2020 National Renewable Energy Laboratory data reports a CAPEX of 1,605,000 US$/MW for a wind project averaging 8.2 m/s. The Lakeside wind project is expected to have an average windspeed of 8 m/s.

Solar. As reference case for the PPA of Solar energy the 150 MWp Sukkur solar plant is selected. This is a FMO co-financed project for which approval is provided in 2021 and construction is expected to finish in 2022. The total project cost is set on 104.3 Million US$. These costs encompass besides construction costs also taxes, insurance, and finance fees. This brings the CAPEX on 695,333 US$/MW.

To illustrate the decline in CAPEX: in 2019 the Gharo solar project finished construction at 972,000 US$/MW.

To compare: the 2020 National Renewable Energy Laboratory data report a CAPEX of 1,600,000 US$/MW.

F.3. Fuel cost (OPEX)
The fuel cost of a powerplant is the cost of fuel to produce one MWh. The fuel cost is calculate using the following formulas:

(1) Energy value [MWh/fuel unit] = Calorific value [MJ/fuel unit] * efficiency / 3600

(2) Fuel cost [$/MWh] = fuel price [$/fuel unit] / energy value [MWh/fuel unit]

The calorific value is the energy released when one fuel unit burns. The efficiency is the ratio in which the energy released from the combustion of energy is converted into electricity. Efficiency is a property of a powerplant. The fuel price paid depends on fuel contracts by the Pakistan government with fossil fuel producing countries. The contracted price is correlated with the worldwide market price for fuel. The fuel price fluctuates over time due to changes in fuel price.

Coal. As reference case for the capital expenditure of coal the 2016 PPA application by the China Power Hub Generation Company is considered.

Fuel prices
The 2016 PPA application determined a total imported coal price of 129.06 US$/Ton. The PPA assumes a mix of 40% Richard Bay (South Africa) Coal, 20% Newcastle-Australia, and 40% Newcastle Indonesia. The average price for the raw material is 90.18 US$/Ton. The remainder of the coal price comprises of marine freight (20 US$/Ton), marine insurance (0.10% of coal price), and other costs (10% of coal price). The domestic Pakistan Coal is priced at 103.17 US$/Ton according to the 2016 PPA application.

According to the BP statistical review (2020, 7) the China Qinhuangdao spot price equalled 85.89 US$/Ton in 2019. The European and USA spot prices are approximately 30% lower.

According to the World Bank (2020b, 10) the imported coal price range between $121 and $171 per Ton and the domestic delved coal range between $13.6 and $54.4 per Ton.

Efficiency
The minimum LHV thermal efficiency of 39% is approved by NEPRA in the PPA contract. According to TRANSFORM (2018) the worldwide coal efficiency is 33%. Modern state-of-the-art plant can achieve 45%, while off-the-shelf plant have efficiency rates of around 40%.

Calorific value
The average calorific values used in the coal powerplant is 25,110 BTUs/Kg. Calorific values of coal can be significantly different depending on the type of coal used.

Table 17: Fuel price calculation for Coal

Fuel source	Caloric value [MJ/Ton]	Powerplant Efficiency [%]	Fuel price [US$/Ton]	Energy value per MWh [MWh/Ton]	Fuel cost [$/MWh]
Coal (Total cost)	25,110	39	129.06	2.7203	47.44
Coal (Imported raw material)	25,110	39	90.18	2.7203	33.15
Coal (Domestic)	25,110	39	13.60 - 103.17	2.7203	5 – 37.93

Model use
Table 17 shows a large price range across sources. Pakistan is currently developing its domestic coal mines to ramp-up the capacity for domestic coal production (NTDC 2020, 273). The share of domestic coal is currently rather slim; therefore, this study calculates with the imported coal price. In the model the raw material coal price of 90.18 US$/MWh is used.

Gas. As reference case for the PPA tariff of Gas the Kolachi Portgen Limited 2019 PPA application is selected.

Fuel prices
The PPA application of Kolachi Porgen Limited in 2019 included an assumed gas price of US$ 7 per MMBTU-HHV. 1 MMBTU equals 28,20 m^3. Therefore, the fuel price in 2019 equalled 0.25 US$/$m^3$. The BP Statistical review (2020, 9) report significant regional differences in gas prices. Japan paid in 2019 9.94 US$/MMBTU (0.35 US$/m^3) while the Netherlands TTF price was 4.45 US$/MMBTU (0.15 US$/M^3). The difference is to a large extent explained by the higher transportation cost of natural gas to Japan. Pakistan also imports gas using ships. Therefore, it makes sense that the gas price for Pakistan is higher than the Netherlands TTF price. Furthermore, the BP statistical review (2020) show a strong fluctuation of energy prices between 4.27 US$/MMBTU in 2002 and 16.75 US$/MMBTU in 2012.

Efficiency
The proposed efficiency of Kolachi Porgen Limited is 58.06%. The 2020 National Renewable Energy Laboratory data for combined cycle gas powerplants average an efficiency of 55%.

Calorific value

The calorific value of natural gas is a standardized gross calorific value of 40 MJ/m^3 (BP 2020, 6).

Table 18: Fuel price calculation for gas

Fuel source	Caloric value [MJ/m^3]	Powerplant Efficiency [%]	Fuel price [US$/$m^3$]	Energy value per MWh [MWh/m^3]	Fuel cost [$/MWh]
Gas	40	58,06	0.25	0.00645	38.75

F.4. Overview of NPV and LCOE data

In the Agent-Based model an investor is restricted to coal, gas, wind and solar as generation types. Therefore, only for those generation assets the Net Present Value (NPV) and Levelized Cost of Electricity (LCOE) is calculated. The values used as initial values in the Agent-Based model is presented in Table 19.

Table 19: NPV and LCOE values at model initialisation. All values are in US$

Generation type	LCOE [US$/MWh]	NPV [US$]
Coal	72.60 (@10%) 79.77 (@12%)	59 M -93 M
Gas	69.88 (@10%) 75.69 (@12%)	233 M 135 M
Wind	41.98 (@10%) 49.33% (@12%)	8 M -3 M
Solar	54.74 (@10%) 64.33 (@12%)	-43 M -52 M

Data comparison. As comparison for the LCOE data retrieved from Pakistan data sources the IEA 2020 LCOE data is used.

Table 20: LCOE comparison for all generation alternatives using three data sources

Generation type	Pakistan LCOE [US$/MWh]	IEA (2020) LCOE [US$/MWh]	Apricum (2014) & ACWA Power (2017) [US$/MWh]
Hydro	No data	68.57[27]	
Nuclear	No data	35.49[28]	
Coal	72.60 (@10%)	90.74[29]	
Gas	69.88 (@10%)	71.88[30]	
Oil	No data	No data	200 (assumption D9)
Wind	41.98 (@10%)	44.82[31]	
Solar	54.74 (@10%)	44.15[32]	
Bagasse/ Biomass	No data	68.20[33]	

Appendix G: Profile cost and VRE cost reduction input variables.

G.1 Profile cost

With a higher share of variable renewable energy in the electricity mix the reliability of VRE sources decline. The costs associated with this reliability decline is expressed in profile cost. The profile

[27] Retrieved from IEA (2020) p64 table 3.16a at 10% discount and India as reference country
[28] Retrieved from IEA (2020) p58 table 3.13b1 at 10% discount and average of all data points
[29] Retrieved from IEA (2020) p56 table 3.12 at 10% discount and India as reference country
[30] Retrieved from IEA (2020) p56 table 3.11b at 10% discount and Italy as reference country
[31] Retrieved from IEA (2020) p62 table 3.15a at 10% discount and India as reference country
[32] Retrieved from IEA (2020) p56 table 3.14 at 10% discount and India as reference country
[33] Retrieved from IEA (2020) p66 table 3.14 at 10% discount and Brazil as reference country

costs included in the Agent-Based Model are derived from the literature review of Heptonstall and Gross (2021) and are presented in the table below.

Table 21: Profile cost for different levels of VRE penetration in the total generation mix.

PROFILE COST VRE	
VRE share	Profile cost [US$/MWh]
<5%	0
5-15%	9.7
15-25%	14.55
25-35%	19,41
35-45%	24.26

G.2 Cost reduction and learning rate VRE

The data presented in the table below is based on information from Our World in Data (2020), National Renewable Energy Laboratory (2020) and IRENA (2017). It presents the average yearly cost reduction and learning rate of VRE. Learning rate is the cost reduction with each doubling of the installed capacity. The relationship between the learning rate and average cost reduction can deviate because the calculations use different variables. Average cost reduction is the yearly average cost reduction cost reduction, the learning rate does not include the time component but looks at the price reduction for each doubling of the installed capacity.

According to future predictions by National Renewable Energy Laboratory (2020) between 2020 – 2045 the average cost reduction per year for solar is 2% (moderate scenario). They assume an average CAPEX reduction between 2020 and 2030 of 5%, after which it drops down to 1% until 2045. For wind National Renewable Energy Laboratory (2020) expect a cost reduction of on average 1.3%.

IRENA (2017) reported a 6% average cost reduction per year for solar and a 3.3% cost reduction for onshore wind during the 2010-2016 period. The World Bank (2020b) electricity market model of Pakistan is based on these figures.

Table 22: VRE cost reduction and learning rate of VRE

VRE COST REDUCTION AND LEARNING RATE VRE		
Generation type	**Average cost reduction per year**	**Learning rate**
Our world in data (2020) backcast		
Solar	21% (2010 -2019)	20.2% (1976 – 2019)
Onshore wind	5.5% (2010 -2019)	23% (2010 – 2019)
National Renewable Energy Laboratory (2020) forecast		
Solar	2%	
Onshore wind (class 6)	1.3%	
IRENA (2017) backcast		
Solar	6% (2010 – 2016)	
Onshore wind	3.3% (2010 – 2016)	9%

Appendix H: Model narrative

This section provides an overview of the model steps. The model narrative is supported by flowcharts that visualise the model procedures. In the model narrative the procedures are bold, and the agents are italic.

The model narrative start with the model setup. Then the yearly investment cycle is explained in four distinct phases: electricity market update, PPA tariff update, investments, and end of year electricity market updates. These phases are executed repeated over the 25-year duration of the model.

H.1 Model setup

The first step of the model is to create the visual representation of Pakistan's electricity sector. layout of the model. Then, all global variables are defined in the **setup** procedure. Then the *investors* are created in **setup-investors.** Three different types are created: DFI, progressive and conservative investors. The only difference between the investor types is the discount rate. Next, *NEPRA* is created in the **setup-NEPRA** procedure. Followed by **setup-Assets** that defines both the initial states and create the initial amount of *assets* per generation type. If the initial set of *assets* is created with a random age the Levelized Cost of Electricity (LCOE) is increased with an efficiency decreasing factor depending on the age of the *asset*. Older *assets* are more expensive than newer *assets.* In Appendix I the state variables of the and their values are presented for the global variables, NEPRA, assets, and investors.

Then three procedures execute calculations that report basic statistics. The **Generation-mix** procedure calculate the share of coal, gas, wind, and solar installed capacity compared with the total installed capacity. Next, the **Calculated-yearly-electricity-output** procedure calculate for each *asset* their yearly electricity production [MWh] depending on their capacity and the capacity factor. The information per *asset* is summed to a total value which equals the total yearly produced electricity. Finally, the **Calculate-contracted-market-price** is a calculation of the contracted market price. This is calculated by dividing the total price of yearly production over the total output.

H.2 Investment cycle

The investment cycle is a set of procedures that are executed, always in the same order, every year. The procedures use the information of the previous year in the calculation of the current year. This could be seen as the model evolving over time.

Electricity market update

The first step is to **update-demand** by multiplying the demand of previous year with the yearly demand growth factor. Then the **generation-mix, Calculate-yearly-electricity-output, Calculate-contracted-market-price** procedures are executed. All three procedures are described in the model setup section. Finally, the **profile-cost** procedure updates the profile cost of VRE integration.

PPA tariff update

The PPA value of previous year is reduced with the fixed PPA decline factor. This means that the different PPA values for the different generation types are reduced with the same factor each year.

Investments

First the fuel cost for the thermal power plants is calculated in the **calculate-fuel-cost** procedure. For this the external variables of the caloric value, fuel price, and plant efficiency for coal and gas power plants is used as input.

Then the *investors* calculate the Net Present Value (NPV) for the generation alternatives in the **calculate-NPV** procedure. Due to a variance in discount rate between investors the resulting NPV values are different. Next, the **construction_change** procedure selects from the positive NPVs one investment for construction. This selection is based on the proportional share of a generation type in the summation of all positive NPVs. If for example solar's NPV is half that of coal, gas, and wind: then solar has a 2/5th chance of being constructed and the others have a 1/5th chance. In the **invest** procedure the investment is really made by the *investor.* Every investor make one 1000 MW investment in a generation alternative. If after a round of investments (3000 MW) the yearly electricity production does not surpass the demand another investment round is made. Prior to this investment round **construction_chance** procedure is run again to select a new investment object.

Finally, all variables used for the NPV calculation is reset in the **reset-NPV-Variables** procedure.

End of year electricity market update

The **end-of-year-update-assets** procedure checks whether an asset should be decommissioned. if an *asset* reaches the maximum lifetime of the generation type the asset is decommissioned and removed from the model. Finally, the **Apply-learning-curve** procedure applies the yearly learning rate for new solar and wind *assets* that results in a reduction of the capital expenditure (CAPEX).

Appendix I: Parameterization

In this section the concepts identified in the model narrative are translated into computer understandable analogues, these are called primitive types. Netlogo has a relative restricted set of possible primitive types. For the model accompanying this research the following primitive types are used: numbers (integer and floating point), strings (string of characters), booleans (True/False), lists and classes (van Dam et al. 2013, 83).

The selected value of the state variable is essential for the model outcome as they are used for input in calculations. The selected values can be dynamic over time, such as the demand curve or be a static input variable unchanged during a model run. There are also values which are chosen randomly such as the age of initial assets at the initialization of the model.

Values of state variables are based on either assumptions or data received from literature. The source by which the value is determined is presented in the comments.

The tables below present all the information about the state variables used in the Netlogo model. Values presented between brackets it represents a range. Values separated by comma's indicate a list.

I.1. State variables divided into Levers and KPIs

Table 23: The parameters which are also policy levers

PARAMETERS: LEVERS				
State variable	Selected Value	Unit	Primitive type	Description, reference, and rationale
rBase	0.10	-	Float	World Bank (2020b) p 121
rConservativeThermal	0.08	-	Float	Experimental variable (rationale in CH.5)
rConservativeVRE	0.12	-	Float	Experimental variable (rationale in CH.5)
rDFI_VRE	0.08	-	Float	Experimental variable (rationale in CH.5)
DFI_Factor_less_investment	2	-	Float	Experimental variable (rationale in CH.5)
PPADeclineThermal	0.02		Float	Experimental variable (rationale in CH.5)
PPADeclineVRE	0.02			Experimental variable (rationale in CH.5))
LearningRateWind	0.09		Float	Experimental variable (rationale in CH.5)
LearningRateSolar	0.15		Float	Experimental variable (rationale in CH.5)

Table 24: The parameters which are also Key Performance Indicators (KPIs)

PARAMETERS: KEY PERFORMANCE INDICATORS				
State variable	Selected Value	Unit	Primitive type	Description, reference, and rationale
ContractedMarketPrice	≥ 0	US$/MWh	Float	The price for electricity
Rgas	[0 – 1]	-	Float	The share of gas in the total electricity mix
Rcoal	[0 – 1]	-	Float	The share of coal in the total electricity mix
RWind	[0 – 1]	-	Float	The share of wind in the total electricity mix

RSolar	[0 – 1]	-	Float	The share of solar in the total electricity mix

I.2. State variables in Netlogo logic

Table 25: Parameters of the global variables in the Netlogo model. (E) = external variable.

PARAMETERS: GLOBALS				
State variable	Selected Value	Unit	Primitive type	Description, reference, and rationale
Demand (E)	129,700,560	MWh/year	Integer	Real demand based on World Bank (2020b); NTDC forecast 2019/20 is 147,941,000. Selected value in line with assumption B5.
DemandGrowth (E)	1.05	-	Float	Average of 2021 – 2030 NTDC projected demand growth (NEPRA 2020, 156)
ContractedMarketPrice	≥ 0	US$/MWh	Float	The price for electricity
Rgas	[0 – 1]	-	Float	The share of gas in the total electricity mix
Rcoal	[0 – 1]	-	Float	The share of coal in the total electricity mix
RWind	[0 – 1]	-	Float	The share of wind in the total electricity mix
RSolar	[0 – 1]	-	Float	The share of solar in the total electricity mix
PositiveNPV?	Initial: True	True/False	Boolean	Used in procedure
HistoricalEfficiency-Decrease (E)	$\frac{1}{0.995554}$	-	Float	(Cui et al., 2019; European Environment Agency., 2015; NEPRA 2020, 17)
TotalProduced	≥ 0	MWh/year	Float	Calculated in procedure: calculate-yearly-electricty-output
CAPEXCoal (E)	1,448,636	US$/MW	Integer	Refer to 'Appendix F' for variable source
CAPEXGas (E)	872,000	US$/MW	Integer	Refer to 'Appendix F' for variable source
CAPEXWind (E)	1,309,600	US$/MW	Integer	Refer to 'Appendix F' for variable source
CAPEXSolar (E)	695,333	US$/MW	Integer	Refer to 'Appendix F' for variable source
EnergyValueCoal	2.7203	MWh/Ton	Integer	Refer to 'Appendix F' for variable source
CaloricValueCoal (E)	25,110	MJ/Ton	Integer	Refer to 'Appendix F' for variable source
PlantEfficiencyCoal (E)	0.39	-	Float	Refer to 'Appendix F' for variable source
FuelCostCoal	35.54	US$/MWh	Float	Refer to 'Appendix F' for variable source
FuelPriceCoal (E)	90.18	US$/Ton	Float	Refer to 'Appendix F' for variable source
EnergyValueGas	0.00645	MWh/m^3	Float	Refer to 'Appendix F' for variable source

CaloricValueGas (E)	40	MJ/m^3	Integer	Refer to 'Appendix F' for variable source
PlantEfficiencyGas (E)	0.5806	-	Float	Refer to 'Appendix F' for variable source
FuelCostGas	38.75	US$/MWh	Float	Refer to 'Appendix F' for variable source
FuelPriceGas (E)	0.25	US$/$m^3$	Float	Refer to 'Appendix F' for variable source
ProfileCostSolar	0	US$/MWh	Integer	Refer to 'Appendix G' for reference/source
ProfileCostWind	0	US$/MWh	Integer	
NPVCorrectionGas	2	-	Integer	Correction factor to normalize NPV value to 1000 MW
NPVCorrectionVRE	2.5	-	Float	Correction factor to normalize NPV value to 1000 MW
CapacityHydro	1000	MW	Integer	Please refer to 'Appendix E' for variable source
LifetimeHydro (E)	50	Years	Integer	Please refer to 'Appendix E' for variable source
CapacityFactorHydro (E)	0.45	-	Float	Please refer to 'Appendix E' for variable source
LCOEHydro (E)	68.57	US$/MWh	Float	Please refer to 'Appendix E' for variable source
CapacityNuclear	1330	MW	Integer	Please refer to 'Appendix E' for variable source
LifetimeNuclear (E)	50	Years	Integer	Please refer to 'Appendix E' for variable source
CapacityFactorNuclear (E)	0.85	-	Float	Please refer to 'Appendix E' for variable source
LCOENuclear (E)	35.49	US$/MWh	Float	Please refer to 'Appendix E' for variable source
CapacityCoal	1000	MW	Integer	Please refer to 'Appendix E' for variable source
LifetimeCoal (E)	34	Years	Integer	Please refer to 'Appendix E' for variable source
CapacityFactorCoal (E)	0.573	-	Float	Please refer to 'Appendix E' for variable source
LCOECoal (E)	72.60	US$/MWh	Float	Please refer to 'Appendix E' for variable source
PPACoalIni (E)	67.57	US$/MWh	Float	Please refer to 'Appendix F' for variable source

CapacityGas	500	MW	Integer	Please refer to ‘Appendix E’ for variable source
LifetimeGas (E)	30	Years	Integer	Please refer to ‘Appendix E’ for variable source
CapacityFactorGas (E)	0.378	-	Float	Please refer to ‘Appendix E’ for variable source
LCOEGas (E)	69.88	US$/MWh	Float	Please refer to ‘Appendix E’ for variable source
PPAGasIni (E)	88.41	US$/MWh	Float	Please refer to ‘Appendix F’ for variable source
CapacityWind	400	MW	Integer	Please refer to ‘Appendix E’ for variable source
LifetimeWind (E)	25	Years	Integer	Please refer to ‘Appendix E’ for variable source
CapacityFactorWind (E)	0.4	-	Float	Please refer to ‘Appendix E’ for variable source
LCOEWind (E)	41.98	US$/MWh	Float	Please refer to ‘Appendix E’ for variable source
PPAWindIni (E)	47	US$/MWh	Float	Please refer to ‘Appendix F’ for variable source
CapacitySolar	500	MW	Integer	Please refer to ‘Appendix E’ for variable source
LifetimeSolar (E)	25	Years	Integer	Please refer to ‘Appendix E’ for variable source
CapacityFactorSolar (E)	0.187	-	Float	Please refer to ‘Appendix E’ for variable source
LCOESolar (E)	54.74	US$/MWh	Float	Please refer to ‘Appendix E’ for variable source
PPASolarIni (E)	32.31	US$/MWh	Float	Please refer to ‘Appendix F’ for variable source
CapacityBio	200	MW	Integer	Please refer to ‘Appendix E’ for variable source
LifetimeBio (E)	30	Years	Integer	Please refer to ‘Appendix E’ for variable source
CapacityFactorBio (E)	0.49	-	Float	Please refer to ‘Appendix E’ for variable source

LCOEBio (E)	68.20	US$/MWh	Float	Please refer to ‘Appendix E’ for variable source
CapacityHFO	1000	MW	Integer	Please refer to ‘Appendix E’ for variable source
LifetimeHFO (E)	30	Years	Integer	Please refer to ‘Appendix E’ for variable source
CapacityFactorHFO (E)	0.08	-	Float	Please refer to ‘Appendix E’ for variable source
LCOEHFO (E)	200	US$/MWh	Float	Please refer to assumption D8
rBase	0.10	-	Float	World Bank (2020b) p 121
rConservativeThermal	0.09	-	Float	Scenario variable
rConservativeDFI	0.11	-	Float	Scenario variable
rDFI_VRE	0.11	-	Float	Scenario variable
DFI_Factor_less_investment	2	-	Float	Scenario variable
PPADecline	0.01		Float	Scenario variable
LearningRateWind	0.09		Float	Scenario variable
LearningRateSolar	0.15		Float	Scenario variable

Table 26: Parameters of the NEPRA agent variables in the Netlogo model.

AGENT PARAMETERS: NEPRA				
State variable	Selected Value	Unit	Primitive type	Description, reference, and rationale
ProductionSurplus-Absolute	≥ 0	MWh	Integer	Calculated based on the total production by the installed assets
ProductionSurplus-Percentage	≥ 0	-	Float	The factor that production surpass demand
PPACoal	≥ 0	US$	Float	Calculate in procedure: PPA-tariff
PPAGas	≥ 0	US$	Float	Calculate in procedure: PPA-tariff
PPASolar	≥ 0	US$	Float	Calculate in procedure: PPA-tariff
PPAWind	≥ 0	US$	Float	Calculate in procedure: PPA-tariff

Table 27: Parameters of the Investors variables in the Netlogo model.

AGENT PARAMETERS: INVESTORS				
State variable	Selected Value	Unit	Primitive type	Description, reference, and rationale
rThermal	[0 – 1]	-	Float	Discount rate depending on type of investor
rVRE	[0 – 1]	-	Float	Discount rate depending on type of investor
Sum_positive_NPV	≥ 0			The total value of the positive NPV's for an investor. Used to calculate which asset is constructed.
ChanceConstructionCoal	[0 – 1]	-	Float	The change an investor invests in coal. Used in procedure: calculate-NPV
ChanceConstructionGas	[0 – 1]	-	Float	The change an investor invests in gas. Used in procedure: calculate-NPV
ChanceConstructionWind	[0 – 1]	-	Float	The change an investor invests in wind. Used in procedure: calculate-NPV
ChanceConstructionSolar	[0 – 1]	-	Float	The change an investor invests in solar. Used in procedure: calculate-NPV
Investment?	Coal, Gas, Wind, Solar	-	String	The string indicates all the possible types to invest in for a investor in that specific round
DiscountlistCoal *	[0-1]	-	Float	Used for NPV calculation in procedure: calculate-NPV
RevenuelistCoal *	≥ 0	US$	String	Used for NPV calculation in procedure: calculate-NPV
DiscountedRevenueCoal*	≥ 0	US$	String	Used for NPV calculation in procedure: calculate-NPV
SumRevenueCoal *	≥ 0	US$	String	Used for NPV calculation in procedure: calculate-NPV

Costlistcoal *	≥ 0	US$	String	Used for NPV calculation in procedure: calculate-NPV
DiscountedCostCoal *	≥ 0	US$	String	Used for NPV calculation in procedure: calculate-NPV
SumCostCoal *	≥ 0	US$	String	Used for NPV calculation in procedure: calculate-NPV
NPVCoal *	≥ 0	US$	Float	Final NPV value calculated in procedure: calculate-NPV

* The same state variables are also included for Gas, Wind and Solar.
The parameters of the assets are specific to the resource of the asset. For the rational behind the selected value please refer to the external variable table.

Table 28: Parameters of the assets variables in the Netlogo model.

AGENT PARAMETERS: ASSET				
State variable	Selected Value	Unit	Primitive type	Description, reference, and rationale
Resource	Hydro, Nuclear, Coal, Gas, Wind, Solar, HFO, Bio	-	List	All resource types present in the energy mix of Pakistan
Age	[0 – 50]	Years	Integer	Random age between zero and the lifetime value of the resource type of the asset
Lifetime	25, 30, 34, 50	Years	Integer	Lifetime values differ per resource type
Capacity	400, 500, 1000, 1330	MW	Integer	Capacity values differ per resource type
CapacityFactor	≥ 0	-	Float	Capacity Factor values differ per resource type
ElecOutput	≥ 0	MWh	Float	Calculated
LCOE	≥ 0	US$/MWh	Float	LCOE values differ per resource type

Appendix K: Exchange rate

The primary currency used for fossil fuel trade and foreign loans is the USD. Therefore, strong changes in the PKR – USD exchange rate influence the solvability of Pakistan and the price for electricity generation. Except from some domestic coal resources Pakistan is fully reliant on imports for their fossil fuel supply to power the thermal powerplants. Figure 44 presents the 10-year USD to PKR exchange rate. Especially the last 4-years the PKR devaluated strongly to the USD making loans harder to pay back and fossil fuel imports more expensive.

Figure 44: 10-year exchange rate USD to PKR. October 2017 shows the start of a strong devaluation of PKR to the dollar. In 10-years' time PKR devaluated with a factor two. Source: XE.com

Appendix L: Certification tests

L.1. Recording and tracking agent behaviour

This section tracks the most important internal calculations. Van Dam et al. (2013) write that this section should be read as a conversation. Appendix H describe the calculation already in this way, to reduce redundance this is not done again in this section.

Net present value

The calculation of the Net Present Value (NPV) is an extensive calculation. Therefore, the calculation is accurately verified. This is done by comparing the output variables of the Netlogo model with an excel calculation. In Netlogo the output variables NPVgas, NPVcoal, NPVsolar, NPVwind are compared with the NPV calculation of the excel file. For this tests the learning rates of solar and wind are set to zero. Otherwise, the capital expenditure variable would change at the first tick. The figures from both sources match. After this the NPV for coal and solar is tracked throughout the model using a plot and printing all the input and output values. On several moments during the model run the input and output variables are copied to excel and compared. This also showed correct calculations by the Netlogo model. Therefore, it is concluded that the NPV calculation is correctly. This calculation test also verifies that the calculation of fuel prices for the thermal powerplants are done correctly.

PPA tariffs by market regulator NEPRA

The calculation of the PPA tariffs is a straightforward, but critical, calculation. The PPA tariffs decline with the same percentage every year. Using a plot, the steady decline is confirmed.

L.2. Single agent testing

To verify whether the agent behaviour is in accordance with the behaviour described in the model conceptualisation *theoretical predictions and sanity checks* are performed (van Dam et al., 2013). This check is type of single agent testing is test whether the model execute the expected behaviour written in the model conceptualisation. Appendix H provides a model narrative that also explains the expected behaviour. This test focus on the investment performed by actors. This part of the code is complicated and extensive. Therefore, a close look at the correct mechanics behind the actors behaviour is an important step to verify the model.

For this test the progressive investor is tracked using print statements in the code, see Figure 45. The printed values are compared with the expected behaviour.

```
NPV Coal Progressive is in [M$]
-221.99890350554608
NPV Gas Progressive is in [M$]
405.0863934345276
NPV Wind Progressive is in [M$]
82.35368053289413
NPV Solar Progressive is in [M$]
-202.17859174606994

[Gas Gas Gas Gas Gas Gas Gas Gas Wind Wind]

Chance Coal by progressive
0
Chance Gas by progressive
0.8310486048826624
Chance Wind by progressive
0.1689513951173376
Chance Solar by progressive
0
I will invest in by progressive
Gas
```

Figure 45: Picture from Netlogo command centre printing values from the progressive investor.

In the investment cycle an investor first calculate the NPV for all four investment alternatives. In Figure 45 the top section show the NPV calculations. The two positive values, pointed towards by the red arrows, are potential investment options. The investor should then construct a list with ten names of generation alternatives that are positive. The third arrow point to the list with investment options and confirms that the list only exists out of generation alternatives with positive NPV. Next, the amount of occurrences of a positive generation alternative should be proportional to the share of its NPV in the summation of all positive NPVs. A quick calculation **confirms** that the list is proportional. Next, randomly a name from the list is selected. In Figure 45 this is gas. Then assigned investment is made by breeding a new asset with the correct type. The Netlogo dashboard shows the new assets. This **confirms** that the right asset is added to the list of assets.

L.3. Extreme value testing

Extreme value testing aims to explore the model behaviour under extreme model input values. The test explores whether the model is robustly built and under which circumstances the model crashes or shows strongly diverting behaviour. Such diverting behaviour or crashed could surface errors in the model.

External variables

- If a PPA value of one of the generation alternatives is set extremely low (5 US$/MWh) no investments are made in the generation alternative.
- If the PPA value of one of the generation alternatives is set extremely high (100 US$/MWh) the generation alternative becomes the majority in the generation mix. The exact share depends per generation alternative. High gas or wind PPAs result in respectively 70% and 85%. For solar and coal this is lower.
- If the learning rate of solar or wind is set extremely high the share of wind or solar becomes the majority in the energy mix.

Appendix M: Pakistan's electricity market stakeholders

Pakistan Electric Power Company (PEPCO)

The Pakistan Electric Power Company Limited (PEPCO) was created in 1998 with the three goals:

(I) To oversee the unbundling and privatisation of WAPDA components. (Bacon 2019, 17)
(II) To manage the transition of WAPDA from a bureaucratic structure to independent corporatised entities ready to work in a competitive environment, consisting of ten generation companies, four distribution companies and a transmission company.
(III) PEPCO should have finished its tasks in two years after establishment. However, it is still overseeing the administrative matters of DISCOs and GENCOs (NEPRA 2020, 25)

The aim at the establishment of PEPCO was that the unbundled companies would become privatised. Privatisation did not happen, and more than twenty years later, it still influences the operations of the unbundled entities (GENCOs, NTDC and DISCOs) to the extent that the boards and managers cannot operate autonomously (Bacon 2019, 17).

Private Power and Infrastructure Board (PPIB)

Under the 1994 'National Power Policy'[34] , a new state-owned institution was created called the Private Power and Infrastructure Board (Bacon 2019, 14). The main functions and responsibilities of the PPIB are:

(I) Providing advice and guidance for the implementation of power plant projects (Bacon 2019, 14)
(II) Support the fuel supply and PPA negotiations.

[34] Officially called: Policy Framework and Package of Incentives for Private Power Generation Projects in Pakistan

(III) Monitoring litigation and, on behalf of the GoP, provide international arbitrage.
(IV) Assist NEPRA in determining and approving tariffs for new private generation investments.

National Transmission and Dispatch Company (NTDC)

After the unbundling of WAPDA the NTDC was founded with the responsibility for the transmission grid (Bacon 2019, 16). The NTDC operates and maintains all the 500 kV grid stations and the 220/500 kV transmission lines (IFC 2016, 17). The purpose of the NTDC as a grid operator is to bring power from the generation companies and supply it to the distribution companies.

Public generation companies (GenCos)

The public generation companies consist of four generation companies (GENCOs), which operate thermal powerplants, and the Pakistan Atomic Energy Commission (PAEC) operates four nuclear power plants. They are all state-owned and overseen by PEPCO. The public generation companies are drivers of circular debt due to the considerable inefficiency of generation and lack of investment (Bacon 2019, 28). The main reason for this inefficiency is the lack of timely overhauling, missing annual scheduled maintenance routines and poor operating schedules (Bacon 2019, 26). This inefficiency is partly caused by the lack of financial incentive to operate efficient. This stems from the fact that all thermal powerplants operate on a 'take-or-pay' basis agreed upon in the PPAs. Therefore, the CPPA is forced to buy from the generation company despite the high cost of electricity or pay capacity payment for idle capacity (NEPRA 2020, 17).

The public GENCOs installed capacity is 25,244 MW in 2020, equalling 65 percent of the total installed capacity (NEPRA 2020, 93). Nuclear accounts for 1,467 MW and contribute 4 percent to total generation capacity.

Water and Power Development Authority (WAPDA)

As a consequence of the 1994 WAPDA Amendment Act, after years of severe power shortages, the vertically integrated utility Water and Power Development Authority was allowed to unbundle (Asian Development Bank [ADB] 2019, 10). The Pakistan Electric Company (PEPCO) was founded to oversee the unbundling process. Initially WAPDA was unbundled into eight distribution companies, three generation companies and a transmission company (ADB 2019, 10). Later, two distribution companies and a generation company were added. WAPDA remains the owner of the large hydropower generation capacity (ADB 2019, 10). WAPDA's current function is electricity generation and falls under the authority of the Ministry of Water.

In 2017, WAPDA had an installed capacity of 6902 MW that equals 24 percent of the total installed capacity (Bacon 2019, 24).

Alternative Energy Development Board (AEDB)

The AEDB is established in 2003 as an autonomous body to promote and facilitate the exploitation of renewable energy projects in Pakistan (IFC 2016, 16). In 2006 the 'policy for Development of Renewable Energy for Power Generation' increased the relevance of the AEDB. The institutions and the 2006 policy aim to promote and attract private investors to set up small hydro, wind, and solar PV plants (Bacon 2019, 17). The current renewable energy mix shows that the policy was predominantly successful in attracting wind energy investment. The AEDB can issue a Letter of Intent for a new RE project that increase the administrative processing speed (The World Bank 2020b, 45).

Appendix N: Drivers of circular debt

Transmission and distribution losses

Transmission and distribution losses (T&D) is the percentage of electricity that is generated but not delivered to a consumer. The reason for T&D losses is either technical or theft. Technical losses are related to low quality or malfunction of components, and theft is related to illegal electricity theft. In Pakistan, the public distribution companies (DISCOs) have T&D losses of 18.32%[35] against the NEPRA target of 15.30% in FY2018 (ADB 2019, 11). This is still very high but already an improvement compared to the extremely high losses of 35 percent during 2009 (Bacon 2019, 37). To put this in perspective, T&D losses of about 5-10% are considered good performance (The World Bank 2020a, 248).

The GoP introduced a policy tool that aimed to improve distribution companies' performance. The sector regulator NEPRA set a target rate of T&D losses for each distribution company. In case the distribution company had higher actual losses that the NEPRA target, the distribution company is not compensated for the excess loss through the tariff differential subsidy (Bacon 2019, 47). The idea of this policy is a financial incentive for distribution companies to increase efficiency. With distribution companies failing to reach T&D losses targets, revenue shortfall increases, reducing cost recovery and increasing circular debt (IMF 2019, 41). As distribution companies are state-owned companies, the debt in the long run is the government's responsibility (The World bank 2020a, 250).

Non-payment of bills

Non-collection or non-payment of bills arise when end-users consume energy but do not pay the charged invoice to their DISCO. The FY 2019-2020 average bill recovery of DISCOs stands at 88.77 percent (NEPRA 2020, 52). To put it into context, a 100% bill recovery is the international standard and government's aim. The main reason for non-payment is, among others, managerial connivance, political pressure, tariff disputes and counterclaims by consumers (ADB 2019, 12). Another complicating factor is that when the GoP increases the electricity tariffs, the non-collection (and theft) of electricity increases (NEPRA 2020, 27). This relation partly offset the envisaged result of the higher consumer tariffs. An example of the private DISCO k-electric shows that improving bill collection is challenging. K-electric introduced a policy where neighbourhoods that pay 80% of the bills get a more reliable power supply. The policy stopped after threats, beatings, and killings (Bacon 2019, 44).

Circular debt burden increases with every unpaid bill because a 100 percent bill collection is assumed in the calculation of the subsidy for DISCOs (Bacon 2019, 62).

[35] Please refer to page 44 of the NEPRA state of industry report to view the T&D losses per individual DISCO.

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