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IIASA Interim Report
December 2004

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Interim Report **IR-04-077**

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December 2004

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Abstract

In this paper we seek to enhance decision making of investments under multiple uncertainties. We assess optimal commitment strategies for future reference of pulp and paper mills given stochastically correlated processes of one input and two output prices. The price processes are consistent with shadow price trajectories of a large scale global energy model. For the detailed engineering model, we developed a frugal forward stochastic optimization procedure to derive optimal commitment strategies.

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Acknowledgments

Financial support from the Kempe Foundations is gratefully acknowledged.

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1 Introduction

Investment strategies in capital and energy intensive industries, like the pulp and paper industry, are driven by long-run price signals and their respective uncertainties. The implementation of climate policies has been identified as one of the main sources of uncertainty for these industries. According to the Intergovernmental Panel on Climate Change (IPCC, 2001a) the actions needed to manage the risks associated with climate change ultimately require substantial long-term commitments to technological change and to mitigation of greenhouse gases (GHG) in all economic sectors. All measures will impact both input and output prices for energy intensive industries and will, thus, alter the competitiveness landscape within and across these industries. The purpose of this paper is to analyze an operation of the benchmark future pulp and paper mills, i.e., mills that are already engineered but not yet built and only run as computer simulations, against market conditions predicted by large scale global energy models.

The option to implement CO_2 capture and storage from biomass energy conversion makes biomass-based industries rich in self-generated biomass residues uniquely equipped to implement negative carbon emission production. Obersteiner *et al.* (2001) have shown that biomass-based industries and biomass-based energy producers could turn the global energy system into a net absorber of CO_2 and thereby substantially increase the flexibility of the global energy system with respect to regulating atmospheric greenhouse gas concentrations. The Kraft pulp industry, which accounts for around 70% of pulp production worldwide (FAO, 2003) belongs to this group of industries and is expected, due to its technological features, to benefit from the implementation of emission permit markets.[1]

This paper evaluates the economic feasibility of CO_2 capture in biomass-based combined heat and power (CHP) systems in a Kraft pulp and paper mill given correlated uncertainties of the biomass fuel, electricity and emission permit prices. For the valuation of the investment decision we will perform a forward stochastic optimization. In our model, a decision variable represents a strategic action or option, which can be adopted by the

[1]For further reading on opportunities for CO_2 reductions in the pulp and paper industry refer to, e.g., STFI, 2000; Khrushch *et al.*, 1999; Martin *et al.*, 2000; Möllersten *et al.*, 2003b; Larson *et al.*, 1999; Mannisto and Mannisto, 1999.

pulp and paper mill owner. More precisely, the following two types of strategic decisions will be considered:

- *Build option:* to invest in building a new system,
- *Switch option:* to switch between already built modules.

The first option refers to a capital investment decision. The owner of the firm must decide which of three possible modules is optimal to build and must decide on the optimal timing of committing the technology. The main occupation of modeling is to find the optimal time to enter the market for GHG abatement. However, we do not stick only to this particular question, we also analyze the complete path of the optimal investment strategies for the chosen time period. In addition, by building a module with CO_2 capture the mill owner exercises the option to enter the revenue generating market for CO_2 permits. The second option refers to adopting an optimal operating strategy.

Solving the model requires that Monte Carlo simulations are performed. In this paper we will introduce a faster and computationally frugal way to perform the computations. We believe that such innovations are necessary in order not to limit the computational time in such complex industry problems.

The paper is organized as follows. Section 2 gives a brief introduction to pulp and paper production and the opportunities for increased overall energy efficiency in pulp and paper mills' CHP systems. In Section 3, an overview of emerging technologies and systems for CO_2 capture and storage is provided. Section 4 then summarizes the main conclusions drawn from previous studies on the incorporation of biomass energy with CO_2 capture and storage in Kraft pulp and paper mills. Section 5 defines the mill environments (market pulp mills and integrated pulp and paper mills) and integrated CHP systems which are modelled in this study. In Section 6 the modeling framework is outlined. Section 7 deals with the modeling of the price processes. The computationally frugal optimization algorithm is introduced in Section 8. In Section 9 the results of our modeling exercise are presented, which are discussed in Section 10 and Section 11 outlines our conclusions.

2 Pulp, Paper and Power

The pulp and paper industry is an important consumer of energy worldwide. The estimated primary energy consumption in this industry worldwide is over 8EJ (Farla *et al.*, 1997). The products of this industry are pulp, paper and board, and paper and board products. Pulp is used as a raw material to produce paper and board. Another important material in paper and board production is recycled fiber from wastepaper. Paper and board can be manufactured in an integrated pulp and paper plant. In many cases, however, the pulp is produced in market pulp mills and then transported to another production site where the paper or board is produced.

Wood pulp is made from trees by a mechanical or chemical pulping process, or a combination of these two pulping processes (semi-chemical pulping). In mechanical pulping, the cellulose fibers are separated by grinding the wood, and the lignin of the wood remains in the pulp. This reduces the fiber quality and limits the use of mechanical pulp to mainly newsprint. In chemical pulping, wood chips are cooked in a solution of chemicals. The wood cellulose fibers are separated by this process as the chemicals dissolve the lignin.

Paper is produced in a paper machine from pulp. The process starts with the forming table where pulp is spread on a screen. A large part of the water is removed on the screen by gravitational force. The sheet of pulp is further dewatered by pressure and heat. Depending on the end use of the paper several coatings may be applied to the sheet.

The dominating type of chemical pulp worldwide is Kraft pulp, which accounts for around 70% of pulp production (FAO, 2003). The Kraft pulp process generates a by-product from fiber extraction known as black liquor, which is a mixture of lignin and inorganic chemicals. Slightly more than half of the biomass entering a Kraft pulp mill is dissolved in the black liquor. In modern Kraft pulp mills the black liquor is burned in recovery boilers that recover important pulping chemicals and produce steam, which is fed to the mill CHP system. The efficient utilization of the black liquor energy content can reduce the Kraft pulp and paper industry's reliance on fossil fuels. In energy efficient Kraft market pulp mills the fuel requirement for the CHP system is typically covered through black liquor and internally generated bark, whereas integrated pulp and paper mills and paper mills need to import fuels to satisfy the process demand for medium pressure (MP) and low pressure (LP) steam. In nearly all Kraft pulp production fossil fuels are still used in lime kilns, although a limited number of kilns have been converted to biofuels (Siro, 1984). Most pulp mills and all integrated mills rely on electricity import to cover the part of their electricity demand that is not satisfied by internal generation.

The pulp and paper industry's ambition is to achieve development towards a "closing" of the process further. This means minimizing the amount of effluents together with reducing the need for additional raw materials and energy. Generally, this can be expected to reduce the heat demand (through improved heat integration), as well as to induce increases in the demand for electricity. In existing Kraft pulp mills with modern CHP systems based on recovery boilers and biomass boilers, electrical efficiencies are fairly low (up to 15%)[2] (Larson *et al.*, 2000). Improved overall energy efficiency and increased electrical efficiency emissions could be accomplished by the introduction of the black liquor integrated gasification combined cycle (BLGCC) (Berglin *et al.*, 1999; Larson *et al.*, 2000; Maunsbach *et al.*, 2001; Larson *et al.*, 1999), which is a promising, although not a commercially available technology. Larson *et al.* (1999) modelled the performance of black liquor and biomass integrated gasification combined cycle in a typical present-day U.S. mill. The results show that electrical efficiencies around 28–29% could be achieved. The higher power-to-heat ratio compared to recovery boilers with steam turbines makes BLGCC particularly attractive in mills with a low process steam demand. With efficient CHP systems based on gasification, and taking predicted efficiency improvements in pulp and paper making into account, Kraft pulp mills and integrated pulp and paper mills could turn into substantial net exporters of electricity (Berglin, 1999; STFI, 2000; Maunsbach, 1999).

3 CO_2 Capture, Transportation and Permanent Storage — Technologies and Potentials

There are technologies under development that separate or "capture" the CO_2 from fuel conversion and store CO_2 or carbon in some form away from the atmosphere for long

[2]Net power output/lower heating value of fuel input. The lower heating value (LHV) is used as the basis for the calculations and numbers presented throughout this paper.

periods of time. Capture, transportation and storage of CO_2 is feasible and technically proven. There is considerable experience accumulated in the chemical and petroleum industries for operating chemical reactors and absorption units used for the capture of CO_2 as well as for CO_2 transportation systems (Chiesa and Consonni, 1999). Several commercial projects involving the injection of CO_2 into reservoirs where it displaces and mobilizes oil (so called enhanced oil recovery) are in commercial operation (Holloway, 2001). A major concern, however, is the reliability and safety of long-term storage (IPCC, 2001b; Ceila and Bachu, 2002). According to the IPCC third assessment report CO_2 capture and storage technologies could give major contributions to CO_2 abatement by 2020 (IPCC, 2001b). This section provides an overview of CO_2 capture, transportation and storage technologies with relevance to biomass conversion in pulp and paper mills.[3]

3.1 Technologies for CO_2 Capture

Processing techniques for the capture of CO_2 are significantly influenced by the concentration (partial pressure) of the gas to be captured. Gas with low CO_2 concentration means that a large amount of inert gas has to be treated which leads to a significant cost and efficiency penalty because of the size of any downstream scrubbing and heat recovery equipment, etc.

Energy conversion systems for solid fuels with CO_2 capture can be divided into four main process groups.

- **Group 1:** Technically mature end-of-pipe solutions with CO_2 capture from the flue gases after the fuel combustion (post-combustion capture).

- **Group 2:** Processes in which the fuel is gasified. CO_2 which is present in the producer gas downstream from the gasifier is captured before the CO_2-lean gas is combusted or converted to refined liquid or gaseous biofuels (pre-combustion capture).

- **Group 3:** Processes in which fuel gasification is followed by a water-gas shift reaction, whereby carbon monoxide (CO) is reacted with water to form CO_2 and hydrogen (H_2).[4] CO_2 present in the producer gas downstream from the water-gas shift reactor is captured before the CO_2-lean hydrogen-rich gas is combusted (pre-combustion capture). Group 3 technologies increase the carbon capture ratio compared to Group 2 technologies. The pre-combustion route also opens up opportunities for "polygeneration", in which, besides electricity and CO_2, additional products are possible. For example, instead of sending H_2 to a turbine, it can be used to fuel a hydrogen economy or used as an excellent feedstock for many chemical processes.

- **Group 4:** Processes based on the combustion of the fuel in oxygen instead of air, using recirculated CO_2 to moderate the combustion temperature. These processes result in a very high CO_2 concentration of the flue gases without

[3] For further discussions on CO_2 capture, transportation and storage see, for example, Parson and Keith (1998); DOE (1999); Williams *et al.* (2000); Grimston *et al.* (2001); Holloway (2001); Freund and Davison (2002); IEA (2002); Lackner (2003).

[4] $CO + H_2O_{vap} \rightarrow CO_2 + H_2 + 44.5\ MJ/Mol_{co}$.

further treatment. However, technology for combustion in an oxygen-rich environment is far from commercialization.

Absorption is the most commonly used technology for capturing CO_2 from gas streams, whereby chemical or physical solvents are used. Chemical absorption, which is likely to be the preferred option with low pressures and CO_2 concentrations typical of Group 1 systems. Chemical absorption, is a proven method for capturing CO_2 from flue gases (post-combustion capture). MEA (monoethylamine) is a typical commercially available chemical absorbent. When a gas is at high pressure and the CO_2 concentration in a gas stream is relatively high, such as the fuel gas from pressurized gasifiers used in some concepts for integrated gasification with combined cycles (IGCC), physical absorption is a more suitable candidate technology. Typical solvents are Selexol (dimethylether of polyethylene glycol) and Rectisol (cold methanol). The energy demand of chemical absorption is mainly due to heat consumption for regeneration of solvents. For physical absorption the main energy demand is for compression and pumping of solvents (Göttlicher and Pruschek, 1997). The gas separation membrane is another promising technology for CO_2 capture from gas streams, which can lead to energy and cost savings. However, much further development is necessary before this technology can be used in large-scale applications.

Although there are commercially available technologies for CO_2 capture, the efficiency and economic performance of biomass energy with CO_2 capture can be improved through integrated process configurations and the development of new technologies.

3.2 CO_2 Storage

A key issue is where CO_2 should be stored. The discussion on CO_2 storage covers the injection of supercritical-state CO_2 into underground geological formations or the deep oceans and technologies for conversion to stable carbonates or bicarbonates. Much further work is required to investigate the permanent storage of CO_2. Deep underground disposal is regarded as the most mature storage option today according to Lindeberg (1999). Suitable candidate underground CO_2 storage locations are exhausted natural gas and oil fields, not exhausted oil fields (so-called enhanced oil recovery), unminable coal formations, and deep saline aquifers (water-containing layers). Lindeberg (1999) points out that the advantage of underground disposal compared with other storage options (such as ocean storage) is that it gives minimum interference with other ecological systems and can provide storage for very long periods of time. International monitoring of current disposal projects will help to evaluate whether underground storage is a safe mitigation option. In one ongoing verification project nearly one million tonnes of carbon dioxide a year are separated from CO_2-rich natural gas and injected into the Utsira formation in the North Sea (Kaarstad, 2000). In Table 1, the global carbon underground storage potential assessment of Grimston *et al.* (2001) is reproduced.

Disposal in the deep oceans has considerable uncertainties regarding potential environmental damage, especially the effects on marine life due to increased acidity and regarding the long-term isolation of the CO_2 (Falkowski *et al.*, 2000). CO_2 injected into seawater at a depth of 3000 meters (m) might be returned to the atmosphere within 250 to 550 years (RCEP, 2000).

Neutralization of carbonic acid to form carbonates or bicarbonates is discussed as a more expensive but safer and more permanent CO_2 storage method (DOE, 1999; Lackner,

Table 1: Potential for carbon storage underground. Source: Grimston *et al.* (2001).

Underground storage	**Storage capacity (Gton C)**	**Retention (years)**
Deep aquifers with structural traps	30–650	>100000
Deep aquifers without structural traps	< 14000	>100000
Depleted oil and gas fields	130–500	>100000
Coalbeds	80–260	>100000
Enhanced oil recovery	20–65	Tens

2003). Neutralization-based storage accelerates natural weathering processes and results in stable products that are common in nature. Improved methods for accelerating carbonation are however needed, as the current best approaches are too costly (Lackner, 2003).

3.3 CO_2 Transportation

Because of the large volumes involved, pipelines are required for the transportation of CO_2 to a storage location once it has been captured (IEA, 2002). Transport of CO_2 can best be done at high pressure in the range of 80 to 140 bars. Compression and pipeline transport of CO_2 is feasible and technically proven. In addition, the use of large tankers might be economically attractive for long distance transportation of compressed/liquefied CO_2 over water (Ekström *et al.*, 1997).

4 CO_2 Balances and Mitigation Costs of Pulp and Paper Mill CHP Systems with CO_2 Capture

The technical CO_2 reduction potential of biomass-based CHP systems in Kraft pulp and paper mills can be enhanced by applying CO_2 capture and permanent storage (Ekström *et al.*, 1997; Möllersten, 2002; Möllersten *et al.*, 2003a–c, 2004). An assessment of the mitigation potential of CO_2 capture and storage in CHP systems of existing standard Kraft market pulp mills was carried out by Möllersten (2002) and Möllersten *et al.* (2003a). The largest reduction potential found was for post-combustion CO_2 capture from recovery boiler and bark boiler flue gases. Significantly lower CO_2 mitigation was achieved by the analyzed BLGCC systems with pre-combustion capture. Note, however, that the analysis was restricted to considering the capture of CO_2 present in the producer gas stream immediately downstream from the gasifier.

Möllersten *et al.* (2004) and Möllersten *et al.* (forthcoming) subsequently investigated the integration of CHP systems with CO_2 capture and storage in market pulp mills and integrated pulp and paper mill environments of predicted future performance with a considerably lower process steam demand than today's existing mills. The reference mills have significantly lower process steam demand than currently existing mills. Furthermore, the studies were an extension of previous analysis in that they considered adding a water-gas shift reaction prior to CO_2 absorption, whereby the availability of CO_2 for capture is raised by reacting CO in the gas stream downstream from the gasifier with water to form CO_2 and H_2 (CO-shift). It was shown that the CO shift increases the CO_2 capture potential of BLGCC to approximately the same level that can be achieved by post-combustion CO_2 capture from recovery boiler flue gases. Hence, steep CO_2 reductions can be achieved through CO_2 capture and storage regardless of whether the CHP system is based on boiler technology with steam turbines or gasification with combined cycle. Note, however, that the analysis of BLGCC systems was restricted to considering the capture of CO_2 present in the producer gas stream immediately downstream from the gasifier[5]

Möllersten *et al.* (2004) and Möllersten *et al.* (forthcoming) also estimated the cost of CO_2 capture for the studied systems. The economic analysis showed lower CO_2 capture costs for BLGCC-based systems compared to systems based on recovery boilers. Moreover, in systems based on BLGCC the capture cost was reduced by adding a CO shift reaction. It is important to note, however, that the CO_2 capture costs were estimated considering only one fixed level of electricity and biomass prices. Such a static analysis provides only limited information about the economic feasibility of the studied technology, since it is reasonable to assume that more stringent CO_2 restrictions will lead to an upward development of electricity and biomass prices along with the price of CO_2.

5 Technical Definition of Studied Mill-Based CHP Systems

The CHP systems that are the subject of further economic evaluation in the present paper are based on Möllersten *et al.* (2004) and Möllersten *et al.* (forthcoming). The studied mill environments and CHP systems are defined below.

5.1 Mill Environment

The modeling of CHP systems in this study is carried out in two different mill environments: a market pulp mill (MPM) and an integrated pulp and paper mill (IPPM). The MPM is based on the "KAM" MPM defined by the Swedish research program "the Ecocyclic Pulp Mill" (STFI, 2000). The KAM MPM is assumed to employ late 1990s state-of-the-art technology in all departments. More specifically, this means that the most modern and energy efficient technologies used in the Nordic countries as of the late 1990s are assumed. The original KAM reference MPM has the capacity to produce 1000 air-dry tonnes pulp per day (ADt/d). In the present analysis the KAM reference MPM was scaled-up to 1550 ADt pulp/d. This corresponds to 2400 tonnes of black liquor/day (dry substance), or 338 MW based on the lower heating value (LHV). The assumption was made that the characteristics of the mill will not change because of the changes of the scale. Thus, energy demands have been scaled-up proportionally to the change in scale. In the KAM MPM, the required process steam is 11 GJ/ADt pulp (Air-Dry tonne pulp) which is a reduction by 24% compared to the 1994 Swedish average. The IPPM, defined by Berglin *et al.* (1999), is an extension of the KAM MPM. The IPMM steam consumption is approximately 5% lower than the average Swedish 1994 fine paper mill. The IPPM in the present study

[5]Group 2 technology according to Section 3.1.

produces 1860 tonnes of paper per day. The process steam and electricity requirements of the MPM and IPPM used in the modeling are presented in Table 2.

Table 2: Process energy requirements of the considered mill environments.

Energy requirement (GJ/ADt end product)		
	Market pulp mill	**Integrated pulp and paper mill**[a]
Electricity	2.5	4.8
Medium pressure steam (12 bar)	4.3	7.5
Low pressure steam (4 bar)	5.7	8.3

[a] 1.2 tonnes of paper are produced for every ADt pulp produced.

5.2 CHP System Configuration

The analysis includes CHP systems based on:

(i) black liquor recovery boiler and biomass boiler with steam turbine technology(RBST), and

(ii) integrated black liquor and biomass gasification with combined cycle technology (BLGCC).[6]

Table 3 summarizes the alternative CHP system configurations considered in this paper.

The cases MPM/RB_1, MPM/RB_2, IPPM/RB_1, and IPPM/RB_2 are based on recovery boiler technology with back-pressure steam turbines. A condensing turbine is used in the case of excess steam production. A supplemental biomass boiler is considered when steam, in addition to that generated by the recovery boiler, is required to satisfy the process steam demand of the mill. Figure 1 illustrates a CHP system with recovery boiler, biomass boiler, and post-combustion flue gas CO_2 capture. The most important assumptions used for the cases based on black liquor recovery and biomass boilers are given in Table 4. In the cases MPM/RB_2 and IPPM/RB_2 CO_2 capture from the boiler flue gases is carried out by chemical absorption. Steam consumption for the regeneration of the chemical absorbent was assumed to be 2880 kJ/kgCO_2 (MP steam). The captured CO_2 is compressed to 80 bar in a two-stage intercooled compressor.

All cases based on black liquor gasification (MPM/BLG_1, MPM/BLG_2, MPM/BLG_3, IPPM/BLG_1, IPPM/BLG_2, and IPPM/BLG_3) are based on a pressurized (approximately 30 bar) high-temperature, oxygen-blown black liquor gasifier. In brief, the syngas is cooled in a quenching bath using the weak wash as coolant, whereby the weak wash is evaporated using the sensible heat of the syngas. The quenching adjusts the fraction of steam in the syngas to ensure an adequate amount of water for a water-gas shift reaction to proceed in

[6] Further in the text we will only use RB as an abbreviation for recovery boiler and biomass boiler with steam turbine technology and BLG as an abbreviation for black liquor and biomass gasification combined cycle technology.

Table 3: Summary of analyzed CHP system configurations.

	Black liquor conversion		Biomass conversion[a]		CO_2 capture[b]			
Case	Boiler	Gasif.	Boiler	Gasif.	None	Post-combust.	Pre-combustion	
							No CO-shift	CO-shift
MPM/RB_1	x		x		x			
MPM/RB_2	x		x			x		
MPM/BLG_1		x		x	x			
MPM/BLG_2		x		x			x	
MPM/BLG_3		x		x				x
IPPM/RB_1	x		x		x			
IPPM/RB_2	x		x			x		
IPPM/BLG_1		x		x	x			
IPPM/BLG_2		x		x			x	
IPPM/BLG_3		x		x				x

[a]Defines the technology used when fuel in addition to black liquor is required to meet process steam demands.
[b]Capture of CO_2 from both black liquor and biomass is considered when applicable.

Table 4: Main assumptions for CHP systems based on boiler technology.

Boilers	
Recovery boiler efficiency (%)	80
Biomass boiler efficiency (%)	90
Steam cycle	
Turbine inlet temperature (°C)	500
Turbine inlet pressure (bar)	90
Mechanical efficiency (%)	98
Isentropic efficiency, expander (%) High pressure/Medium pressure	85/87
Feed water temperature (°C)	120

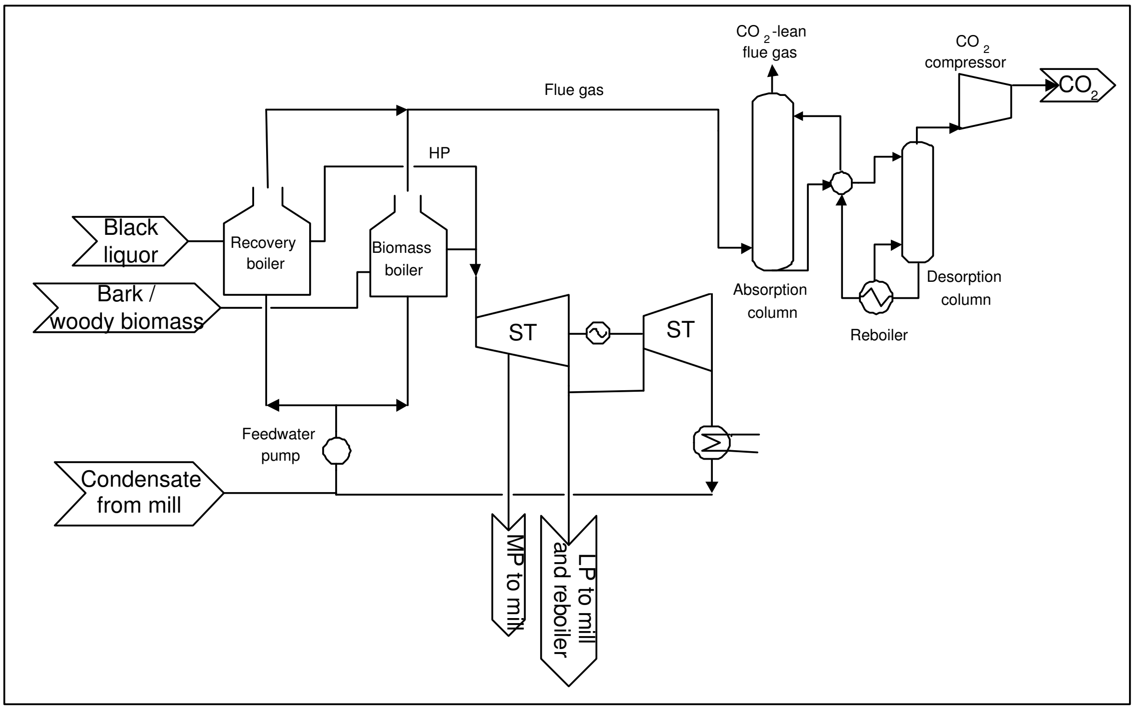


Figure 1: CHP system based on boiler and steam turbine technology. The CHP system in the figure includes post-combustion CO_2 capture.

a downstream CO shift reactor. In the cases MPM/BLG$_3$ and IPPM/BLG$_3$ a CO shift reaction takes place in a high-temperature reactor and a low-temperature reactor in series. In the cases MPM/BLG$_2$, MPM/BLG$_3$, IPPM/BLG$_2$, and IPPM/BLG$_3$ CO_2 capture is carried out in physical absorption units upstream from the gas turbine combustion chamber. The physical absorption units resemble the Selexol process. The work consumed for CO_2 absorption depends on the partial pressure of the CO_2 in the gas mixture. In this study the work required amounts to 0.14 MJ/kg of CO_2 captured. The captured CO_2 is compressed to 80 bar in a two-stage intercooled compressor. After the clean-up section the syngas is used to fuel a gas turbine for power generation. Normally, CO_2 plays a role as coolant in the combustion. With the capture of CO_2 more inert gas (air) is needed as coolant, which leads to a larger work requirement in the compressor. In addition, when CO is converted to CO_2 and H_2 some of the chemical energy is converted to reaction heat which means that the total energy content of the fuel to the combustor decreases. Part of the reaction heat (approximately 44.5 MJ/Mol$_{co}$) can be recovered and thus made useful in the process. The exhaust gas from the gas turbine is recovered in a heat recovery steam generator (HRSG) and the generated steam is used for process steam needs in the mills, either directly or via a back-pressure steam turbine which generates additional electricity. When additional fuel is required to satisfy the process steam demand a supplemental biomass integrated gasifier with combined cycle (BGCC) is considered (as illustrated in Table 3). Figure 2 illustrates a CHP system with black liqour gasifier, biomass gasifier, CO-shift, and pre-combustion CO_2 capture. The main assumptions of the CHP systems based on gasification are given in Table 5.

Table 5: Main assumptions for CHP systems based on gasification technology.

Gasifiers				
	Black liquor		**Biomass**	
Cold gas efficiency (%)	77		77	
	Syngas properties			
	Raw gas	**After quench**	**Raw gas**	**After quench**
Temperature (°C)	950	211	900	209
Pressure (bar)	32	25	27	25
Composition (mol %)				
N_2	0.2	0.1	0.2	0.1
CO	29.5	13.5	30.0	13.0
CO_2	14.6	6.7	24.2	10.4
H_2O	22.0	64.3	15.9	63.7
H_2	31.1	14.2	24.1	10.4
H_2S	1.5	0.7	0.0	0.0
CH_4	1.1	0.5	5.6	2.4

Gas turbine	
Turbine inlet temperature (°C)	1250
Pressure ratio	17
Mechanical efficiency (%)	98
Isentropic efficiency, expander (%)	92
Isentropic efficiency, compressor (%)	87
Steam cycle Turbine inlet temperature (°C)	440
Turbine inlet pressure (bar)	66
Mechanical efficiency (%)	98
Isentropic efficiency, expander (%) High pressure/Medium pressure	85/87
Pinch temperature difference of HRSG (°C)	15
Feed water temperature (°C)	120

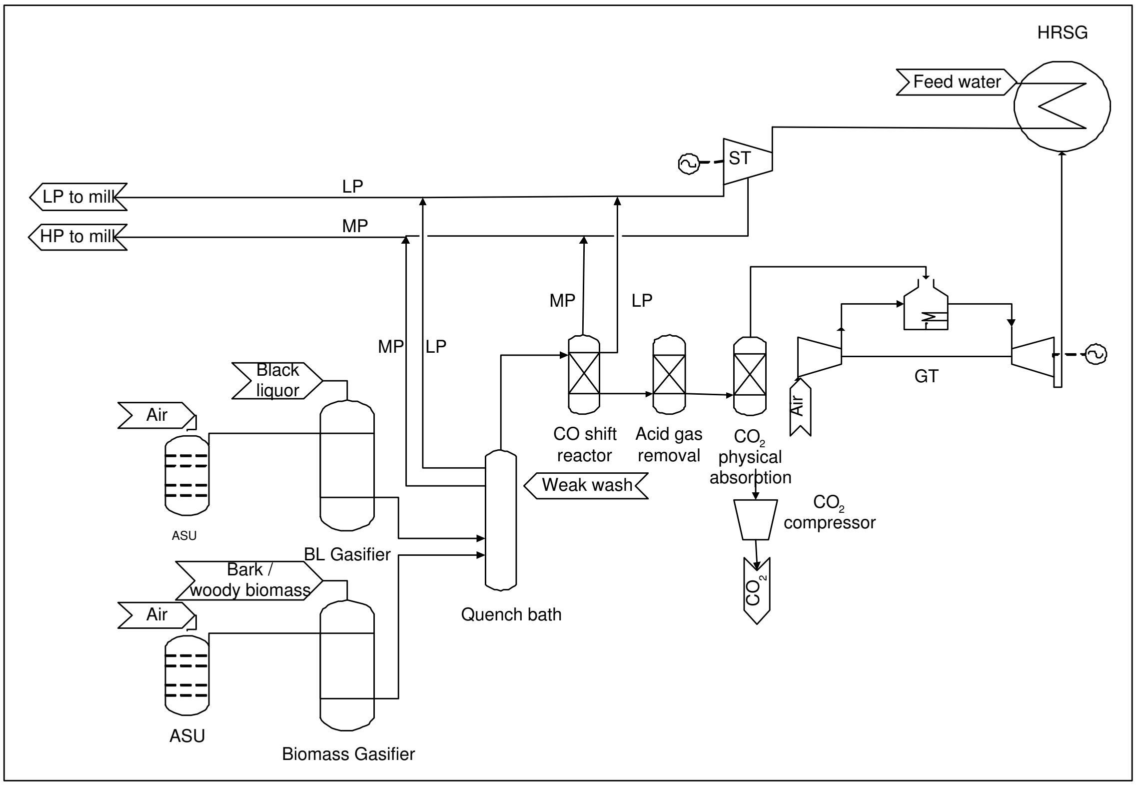


Figure 2: CHP system based on gasification and combined cycle technology. The CHP system in the figure includes pre-combustion CO_2 capture.

5.3 CHP System Performance

The performance of the analyzed CHP systems is summarized in Tables 6 (MPM cases) and 7 (IPPM cases). The tables show the mill-integrated systems' performance with regard to fuel requirement, CO_2 capture rate (when applicable), electricity production and overall energy efficiency. Note that in all cases the mills' process steam demand is satisfied precisely.

Table 6: Performance of the MPM CHP systems (Pulp production 1550 ADt/d).

	MPM /RB$_1$	**MPM /RB$_2$**	**MPM /BLG$_1$**	**MPM /BLG$_2$**	**MPM /BLG$_3$**
Black liquor (MW)	338				
Bark & woody biomass (MW)	0	74	0	0	0
CO_2 recovery (%)	0	90	0	31	90
CO_2 capture rate (kg CO_2/s)	0	33	0	10	27
MP steam to mill (12 bar-t/h)	101				
LP steam to mill (4.5 bar-t/h)	137				
Power consumption for CO_2 absorption (MW)	N.A.	N.A.	N.A.	2	4
Heat consumption for CO_2 separation (MW)	N.A.	96	N.A.	N.A	N.A.
Internal power consumption					
CO_2 compressor (MW)	N.A.	16	N.A.	4	13
Air separation unit (ASU) (MW)	N.A.	N.A.	5	5	5
Others (MW)	0	0	10	10	10
GT output (MW)	N.A.	N.A.	100	99	93
ST output (MW)	53	62	21	16	10
Net electricity output(MW)	53	46	106	94	71
Mill electricity consumption (MW)	39				
Electricity surplus (MW)	14	7	67	55	32
Electricity surplus (MWh/ADt pulp)	0.2	0.1	1.0	1.0	0.5
Electrical efficiency (%)	16	11	31	28	21
Total efficiency (%)	60	48	76	72	65

5.3.1 CHP System Capital Costs

Capital cost for the system components are based on estimates by Möllersten *et al.* (2004) and Möllersten *et al.* (forthcoming). The original cost data derives from several literature sources (Larson *et al.*, 2000; STFI, 2000; Warnqvist, 2000; Brandberg *et al.*, 2000; Williams,

Table 7: Performance of the IPPM CHP systems (Paper production 1860 ADt/d)[a].

	IPPM /RB_1	IPPM /RB_2	IPPM /BLG_1	IPPM /BLG_2	IPPM /BLG_3
Black liquor (MW)	338				
Bark & woody biomass (MW)	80	289	114	114	184
CO_2 recovery (%)	0	90	0	33	90
CO_2 capture rate (kg CO_2/s)	0	52	0	14	45
MP steam to mill (12 bar-t/h)	176				
LP steam to mill (4.5 bar-t/h)	200				
Power consumption for CO_2 absorption (MW)	N.A.	N.A.	N.A.	3	6
Heat consumption for CO_2 separation (MW)	N.A.	150	N.A.	N.A	N.A.
Internal power consumption					
CO_2 compressor (MW)	N.A.	24	N.A.	6	20
Air separation unit (ASU) (MW)	N.A.	N.A.	6	6	7
Others (MW)	0	0	14	16	16
GT output (MW)	N.A.	N.A.	135	135	146
ST output (MW)	58	96	0	0	16
Net electricity output(MW)	58	72	115	107	113
Mill electricity consumption (MW)	74				
Electricity surplus (MW)	-16	-2	42	33	39
Electricity surplus (MWh/ADt pulp)	-0.2	0	0.5	0.5	0.5
Electrical efficiency (%)	14	11	25	24	22
Total efficiency (%)	70	49	78	76	68

[a]The turbine is fuelled with predominantly H_2. No commercial gas turbines exist that run on H_2. Future options include commercial gas turbines with combustion temperature control through N_2 injection into the combustion chamber, and so-called hydrogen combustion turbines. A 10% increase of the specific capital cost was assumed for the H_2 fuelled gas turbine.

2002; IEA, 2002; David and Herzog, 2000). Tables 8–11 present the estimated capital costs. A scale factor of 0.7 was used to adjust capital costs for size. An estimated initial accuracy of the source cost data is approximately 30%.

Table 8: Estimated capital costs of MPM/RB CHP systems [MUSD].

Component	**MPM/RB$_1$**	**MPM/RB$_2$**
Recovery boiler island excluding steam turbine	84	84
Biomass boiler island excluding steam turbine	—	11
Steam turbine and generator	14	16
CO_2 absorption	—	74
CO_2 compressor	—	9
Total	**98**	**194**

Table 9: Estimated capital costs of MPM/BLG CHP systems [MUSD].

Component	**MPM/BLG$_1$**	**MPM/BLG$_2$**	**MPM/BLG$_3$**
Black liquor gasification island	74	74	74
Biomass gasification island	—	—	—
Shift reactor absorption	—	—	14
CO_2	—	7	14
Gas turbine	38	38	42
HRSG	13	13	13
Steam turbine	7	6	4
CO_2 compressor	—	4	10
Total	**132**	**142**	**167**

The model also allows for switching between modules. The switching costs were estimated to be 15% of the capital cost for components that need to be switched from off-state into an on-state and 10% of capital cost for components, which are switched from on-state into off-state.

5.3.2 The Cost of CO_2 Transportation and Storage

The cost of CO_2 transportation was determined using a model issued by the IEA GHG R&D Programme (IEA, 2002). The model calculates capital cost, fixed and variable operating costs for the pipelines and injection wells, as well as booster compressor requirements. CO_2

Table 10: Estimated capital costs of IPPM/RB CHP systems [MUSD].

Component	**IPPM/RB$_1$**	**IPPM/RB$_2$**
Recovery boiler island excluding steam turbine	84	84
Biomass boiler island excluding steam turbine	11	41
Steam turbine and generator	18	24
CO_2 absorption	—	102
CO_2 compressor	—	12
Total	**113**	**263**

Table 11: Estimated capital costs of IPPM/BLG CHP systems [MUSD].

Component	**IPPM/BLG$_1$**	**IPPM/BLG$_2$**	**IPPM/BLG$_3$**
Black liquor gasification island	74	74	74
Biomass gasification island	53	53	75
Shift reactor	—	—	20
CO_2 absorption	—	8	20
Gas turbine	47	47	57
HRSG	16	16	18
Steam turbine	—	—	6
CO_2 compressor	—	5	13
Total	**190**	**203**	**283**

injection is assumed to take place in CO_2-retaining aquifers with negligible seepage back to the atmosphere and the depth of the injection wells was set to 1000 m. Capital costs for CO_2 transportation were annualized using an interest rate of 10% and a plant life of 25 years (i.e., 11% capital charge rate). The geographical location of the projects was selected to Europe, which represents an average to high cost level in the model, and the terrain was assumed to be cultivated land, representing an average cost level. For illustration purposes, Figure 3 shows CO_2 transportation and storage costs calculated with the model for some selected CO_2 flow rates and transportation distances.

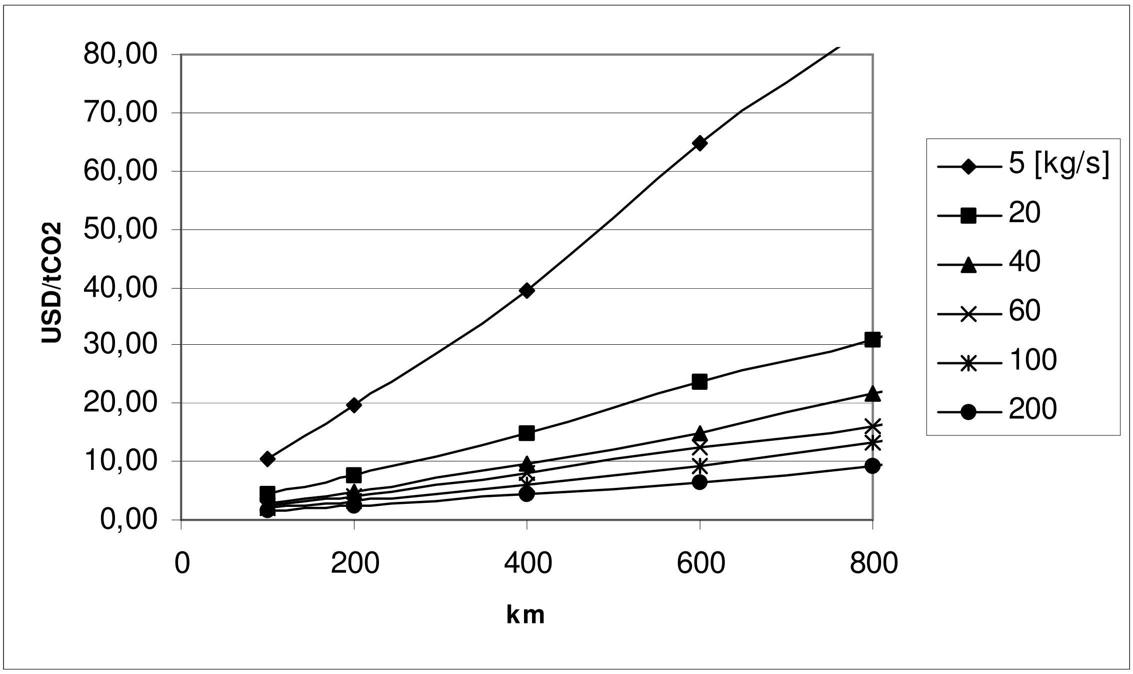


Figure 3: Cost of CO_2 transportation and storage.

6 Modeling Framework

In this section we develop a model for evaluating a complex capital budgeting problem. The aim is to optimize the pulp mill owner's decisions. Two main options will be considered. The first belongs to the category of the capital options: an option to invest in building a new module (system). There are two possibilities of how the new module can be built. The owner can either build an entire new module or, if at least one system has already been built, invest only in the components that are necessary for adding to an already built module. The second option deals with the mill's operating strategy. Once a module has been built, we assume that within the same investment the pulp mill owner has the flexibility to activate it again after having been deactivated if he finds it profitable. This kind of the option we call a *switch option*.

6.1 Preliminaries and Notation

The notation and theorems focus on the BLGcase (that is the case of three distinct modules). They are, nonetheless, applicable also for the RBcase (that is the case of two distinct modules).

6.1.1 Costs

Each BLG module consists of parts. Let BLG_i for $i = 1, 2, 3$ denote the set of parts necessary to build the particular module. Some parts are, however, contained in more than one module (and can be reused). Let $X_0 = \mathrm{BLG}_1 \cup \mathrm{BLG}_2 \cup \mathrm{BLG}_3$ be the set of all parts that we are interested in.

Let $\mathbb{X} = \mathcal{P}(X_0)$ be the set of all subsets of X_0. Then $\mathbb{X}$ is a σ-algebra. Let c^c be a measure on $\mathbb{X}$. The meaning of $c^c(A)$ is the direct capital cost necessary to build all parts in A. Thus, e.g. , $c^c(\mathrm{BLG}_1)$ is the capital cost for building the module BLG_1 and $c^c(\mathrm{BLG}_1 \setminus \mathrm{BLG}_2)$ is the capital cost for building BLG_1 as add-on to an already built BLG_2. The X_0 serves as generators set: the measure c^c is completely defined when non-negative real values are assigned to elements of X_0. In reality, one however does not invest in separate BLG parts.

Hence, it is reasonable to split X_0 into the following "structure-describing" subsets:

$$\begin{aligned}X_0 = {} & \big(\mathrm{BLG}_1 \setminus (\mathrm{BLG}_2 \cup \mathrm{BLG}_3)\big) \cup \big(\mathrm{BLG}_2 \setminus (\mathrm{BLG}_1 \cup \mathrm{BLG}_3)\big) \cup \big(\mathrm{BLG}_3 \setminus (\mathrm{BLG}_1 \cup \mathrm{BLG}_2)\big) \cup \\ & \cup \big((\mathrm{BLG}_1 \cap \mathrm{BLG}_2) \setminus \mathrm{BLG}_3\big) \cup \big((\mathrm{BLG}_1 \cap \mathrm{BLG}_3) \setminus \mathrm{BLG}_2\big) \cup \big((\mathrm{BLG}_2 \cap \mathrm{BLG}_3) \setminus \mathrm{BLG}_1\big) \cup \\ & \cup \big(\mathrm{BLG}_1 \cap \mathrm{BLG}_2 \cap \mathrm{BLG}_3\big).\end{aligned} \tag{1}$$

For our purposes, it suffices to prescribe the values of c^c on the above subsets of X_0 — we will never be interested in smaller sets of BLG parts than those given above. With this definition we compute, e.g. , $c^c(\mathrm{BLG}_1 \setminus \mathrm{BLG}_2)$ as:

$$c^c(\mathrm{BLG}_1 \setminus \mathrm{BLG}_2) = c^c(\mathrm{BLG}_1 \setminus (\mathrm{BLG}_2 \cup \mathrm{BLG}_3)) + c^c((\mathrm{BLG}_1 \cap \mathrm{BLG}_3) \setminus \mathrm{BLG}_2).$$

Nonetheless, only some elements of $\mathbb{X}$ are to be understood as feasible capital investment actions (e.g. , one cannot invest in $\mathrm{BLG}_1 \cap \mathrm{BLG}_2 \cap \mathrm{BLG}_3$ as its first action). Therefore, the feasible capital investment actions are in fact the following:[7]

$$\begin{aligned}\mathcal{A}_c = \{ & \mathrm{BLG}_1, \mathrm{BLG}_2, \mathrm{BLG}_3, \\ & \mathrm{BLG}_1 \setminus \mathrm{BLG}_2, \mathrm{BLG}_1 \setminus \mathrm{BLG}_3, \mathrm{BLG}_2 \setminus \mathrm{BLG}_1, \\ & \mathrm{BLG}_2 \setminus \mathrm{BLG}_3, \mathrm{BLG}_3 \setminus \mathrm{BLG}_1, \mathrm{BLG}_3 \setminus \mathrm{BLG}_2, \\ & \mathrm{BLG}_1 \setminus (\mathrm{BLG}_2 \cup \mathrm{BLG}_3), \mathrm{BLG}_2 \setminus (\mathrm{BLG}_1 \cup \mathrm{BLG}_3), \mathrm{BLG}_3 \setminus (\mathrm{BLG}_1 \cup \mathrm{BLG}_2)\}.\end{aligned}$$

The meaning is straightforward: a module is built with the assumption that some other modules exist, e.g. , by $\mathrm{BLG}_2 \setminus (\mathrm{BLG}_1 \cup \mathrm{BLG}_3)$ the pulp mill owner wants to build module BLG_2 assuming that modules BLG_1 and BLG_3 have already been built. Hence, the owner needs to invest in BLG-parts of $\mathrm{BLG}_2 \setminus (\mathrm{BLG}_1 \cup \mathrm{BLG}_3)$ only.

[7] Note that the pulp mill owner decides only to build some BLG module (say BLG_3) *at the respective moment*. This investment decision will then be expressed by the corresponding $\mathcal{A}_c$ action (say $\mathrm{BLG}_3 \setminus \mathrm{BLG}_1$ if module BLG_1 (but not BLG_2) has already been built earlier).

When the capital investment action is performed, the just-built module is automatically *activated*. Let the module activated by action $a \in \mathcal{A}_c$ be denoted by $a^{\mathbf{on}}$. Thus, e.g. , $\mathrm{BLG}_1^{\mathbf{on}} = \mathrm{BLG}_1$ and $(\mathrm{BLG}_2 \setminus (\mathrm{BLG}_1 \cup \mathrm{BLG}_3))^{\mathbf{on}} = \mathrm{BLG}_2$. The set of modules assumed to be already present by an action $a \in \mathcal{A}_c$ will be denoted by $\mathbf{present}(a)$. For example, $\mathbf{present}(\mathrm{BLG}_1) = \emptyset$ and

$$\mathbf{present}(\mathrm{BLG}_2 \setminus (\mathrm{BLG}_1 \cup \mathrm{BLG}_3)) = \{\mathrm{BLG}_1, \mathrm{BLG}_3\}.$$

Besides capital investment actions, further allowed actions are the *switch actions*. Let:

$$\begin{aligned}\vec{\mathcal{A}} = \{\, & \mathrm{BLG}_1 \to \mathrm{BLG}_2, \mathrm{BLG}_1 \to \mathrm{BLG}_3, \mathrm{BLG}_2 \to \mathrm{BLG}_1, \\ & \mathrm{BLG}_2 \to \mathrm{BLG}_3, \mathrm{BLG}_3 \to \mathrm{BLG}_1, \mathrm{BLG}_3 \to \mathrm{BLG}_2\}\end{aligned}$$

be the set of switch actions. The meaning is again straightforward: with $\mathrm{BLG}_i \to \mathrm{BLG}_j$ one wants to activate the earlier built module BLG_j assuming that the module BLG_i has been active so far. Therefore, operators $(.)^{\mathbf{on}}$ and $\mathbf{present}(.)$ can naturally be extended also to cover $a \in \vec{\mathcal{A}}$ as: $(\mathrm{BLG}_i \to \mathrm{BLG}_j)^{\mathbf{on}} = \mathrm{BLG}_j$ and $\mathbf{present}(\mathrm{BLG}_i \to \mathrm{BLG}_j) = \{\mathrm{BLG}_i\}$.

Switches (similarly as capital investments actions) are in general not free of charge. This is described by a switch-cost function:

$$\vec{c}\colon \vec{\mathcal{A}} \to \mathbb{R}_0^+.$$

Sometimes it is necessary to pay a switch cost even when the module is built for the first time. The cost of a capital investment action $a \in \mathcal{A}_c$ may then either be $c^c(a)$ or $c^c(a)$ increased by some additional cost, depending on the module active so far.

Therefore, let:

$$\begin{aligned}\vec{\mathcal{A}_c} = & \{(a|\,\mathrm{BLG}_i) \mid i = 1,2,3, a \in \mathcal{A}_c, \mathrm{BLG}_i \in \mathbf{present}(a)\} \cup \\ & \cup \{(\mathrm{BLG}_i \mid \emptyset) \mid i = 1,2,3\}.\end{aligned}$$

The meaning of $(a \mid \mathrm{BLG}_i)$ is “perform a with assumption that the module BLG_i has been active so far”. Similarly, $(\mathrm{BLG}_i \mid \emptyset)$ is used if BLG_i is an initial action (i.e. , there is no module active so far). We will often shortcut $(\mathrm{BLG}_i \mid \emptyset)$ to just BLG_i — the precise meaning will be clear from the context. Finally, denote by $\mathcal{A} = \vec{\mathcal{A}_c} \cup \vec{\mathcal{A}}$ the set of all *actions* that can be performed at a particular time.

With this notation in mind we define the *cost function* $c\colon \mathcal{A} \to \mathbb{R}_0^+$ as:

$$\begin{aligned} c(a) &= \vec{c}\,(a) && \text{for } a \in \vec{\mathcal{A}} \\ c(\mathrm{BLG}_i \mid \emptyset) &= c^c(\mathrm{BLG}_i) && \\ c(a \mid \mathrm{BLG}_i) &= c^c(a) + c^{\mathrm{add}}(a \mid \mathrm{BLG}_i) && \text{for } (a \mid \mathrm{BLG}_i) \in \vec{\mathcal{A}_c} \end{aligned}$$

where $c^{\mathrm{add}}(a \mid \mathrm{BLG}_i)$ is additional switching cost necessary to pay by capital investment (specified as input parameter to the model). Note that $c^{\mathrm{add}}(a \mid \mathrm{BLG}_i)$ is usually bound to some standard switching cost, although this is not a necessary condition.

6.1.2 Strategies

We are interested in the optimal strategy of actions of $\mathcal{A}$ performed at each time point within time horizon T. Any capital investment to any BLG part is effective until time T_{retire} only (we assume that T is the multiple of T_{retire}). After time T_{retire} expires the capital investment must be renewed if the pulp mill owner wishes to use a particular BLG module further on. Actually, the pulp mill owner divides the time scale $1, \ldots, T$ into independent periods of maximum length T_{retire} (the division points will be denoted as the *gasification points*). No module and no technical part of it can survive from one such *gasification* period onto another one — the periods are completely independent and can hence be independently optimized — the optimal strategy for the whole time span $1, \ldots, T$ is then archived by optimal strategies in each gasification period. The periods can actually be shorter than T_{retire} as it might sometimes be optimal to retire the module prematurely and start a new gasification period instead of adding investments to almost retired equipment. At each moment one can perform at most one action from $\mathcal{A}$ (performing two actions in the same time is not allowed).

Therefore a *strategy* for the time span $1, \ldots, T$ is the pair $(\mathbf{gp}, \mathbf{a})$ of gasification points $\mathbf{gp}$ and performed actions $\mathbf{a}$ where

- $\mathbf{gp}$ is a non-empty finite rising sequence of numbers from $\{1, \ldots, T\}$ starting with 1;
- and $\mathbf{a}$: $\{1, \ldots, T\} \to \mathcal{A} \cup \{\text{stay}\}$ is the prescription of actions performed in a particular time.

Thus, the gasification periods are

$$\langle \mathbf{gp}(1), \mathbf{gp}(2) - 1 \rangle, \langle \mathbf{gp}(2), \mathbf{gp}(3) - 1 \rangle, \ldots, \langle \mathbf{gp}(\#_{\mathbf{gp}} - 1), \mathbf{gp}(\#_{\mathbf{gp}}) - 1 \rangle, \langle \mathbf{gp}(\#_{\mathbf{gp}}), T \rangle$$

(in this notation $\#_{\mathbf{gp}}$ denotes the number of elements in $\mathbf{gp}$).

With respect to given $\mathbf{gp}$ we can define for each time point $t \in \{1, \ldots, T\}$ the starting and ending time of the gasification period the respective time-point lies in as:

$$\begin{aligned}\mathbf{period\_begin}(\mathbf{gp}, t) &= \max\Big(\{\tau \mid \tau \in \mathbf{gp}, \tau \leq t\}\Big)\\ \mathbf{period\_end}(\mathbf{gp}, t) &= \min\Big(\{\tau - 1 \mid \tau \in \mathbf{gp}, \tau > t\} \cup \{T\}\Big).\end{aligned}$$

At each time point the pulp mill owner either takes some action from $\mathcal{A}$ or takes no action at all (i.e. , he/she takes action "stay") not changing the state of the pulp mill. Thus, we can define the *running strategy* determined by $(\mathbf{gp}, \mathbf{a})$ — the decision of which module will be active at each respective time:

$$\mathbf{rs}(\mathbf{a}, t) = \begin{cases} \mathbf{a}_t^{\mathbf{on}} & \text{if } \mathbf{a}_t \in \mathcal{A} \\ \mathbf{rs}(\mathbf{a}, t-1) & \text{if } \mathbf{a}_t = \text{stay}\,. \end{cases}$$

For the sake of convenience we may define $c(\text{stay}) = 0$.

A strategy $(\mathbf{gp}, \mathbf{a})$ is feasible if the following conditions are met:

$$\begin{aligned}&\mathbf{gp}(i+1) - \mathbf{gp}(i) \leq T_{\text{retire}} \text{ for } i = 1, \ldots \#_{\mathbf{gp}} - 1\\ &T + 1 - \mathbf{gp}(\#_{\mathbf{gp}}) \leq T_{\text{retire}}\end{aligned} \tag{2}$$

and for each $t = 1, \ldots, T$

$$\text{if } t \in \mathbf{gp} \text{ then } \mathbf{a}_t \neq \text{stay} \tag{3}$$

$$\text{if } \mathbf{a}_t \in \vec{\mathcal{A}} \text{ then } \exists \tau < t : \mathbf{period\_begin}(\mathbf{gp}, t) = \mathbf{period\_begin}(\mathbf{gp}, \tau) \wedge \mathbf{a}_t^{\mathbf{on}} = \mathbf{a}_\tau^{\mathbf{on}} \tag{4}$$

$$\begin{aligned} &\text{if } \mathbf{a}_t \in \vec{\mathcal{A}}_c \text{ then } \forall m : m \in \mathbf{present}(\mathbf{a}_t) \iff \\ &\qquad \iff \exists \tau < t : \mathbf{period\_begin}(\mathbf{gp}, t) = \mathbf{period\_begin}(\mathbf{gp}, \tau) \wedge \mathbf{a}_\tau^{\mathbf{on}} = m \end{aligned} \tag{5}$$

$$\text{if } \mathbf{a}_t \in \vec{\mathcal{A}}_c \text{ then } \forall \tau : \mathbf{period\_begin}(\mathbf{gp}, t) \leq \tau < t \implies \mathbf{a}_\tau^{\mathbf{on}} \neq \mathbf{a}_t^{\mathbf{on}} \tag{6}$$

$$\text{if } \mathbf{a}_t = \text{BLG}_i \to \text{BLG}_j \text{ then } \mathbf{rs}(\mathbf{a}, t-1) = \text{BLG}_i \tag{7}$$

$$\text{if } \mathbf{a}_t = (a \mid \text{BLG}_i) \text{ then } \mathbf{rs}(\mathbf{a}, t-1) = \text{BLG}_i\,. \tag{8}$$

The meaning of those conditions is the following:

- (2) claims that the gasification points must occur at distance T_{retire} or less.
- (3) claims that at the beginning of the gasification period some action (actually a build-action) must be taken.
- (4) claims that the pulp mill owner can only switch to a module that has been built earlier in the same gasification period.
- According to (5) the build-action must be consistent with already built modules.
- A module can be built only once in each gasification period, as (6) claims.
- And finally, according to (7) and (8), if an action assumes that some module has been active so far then it must be true.

6.1.3 Price Processes

So far we have considered the module setup. However, once the module is active it operates and perhaps produces profit (i.e. , the *operational profit*). This is ruled by price processes that vary in time: the *electricity price* p_t^e, the *biomass price* p_t^b, and the CO_2 *price* p_t^c. The values of price processes are generated (simulated), they bring the uncertainty to the model. For the algorithm optimizing the pulp mill owner behavior they are, however, the fixed input parameters (see Section 7 for details on the price processes simulation).

6.1.4 Learning

It is not a surprise that any technology that is used for some time turns out to be cheaper and cheaper. This effect is called *learning*. We will use learning for considering the costs by introducing the *learning rate* R. This means that any capital investment cost, switching cost or switching cost additionally paid by capital investment or any other technology-related cost will be decreased by the factor $1/(1 + R)^t$, if realized at point in time t.

6.1.5 Operational Profit

When the module BLG_i operates it produces a fixed amount q_c of CO_2 and surplus electric power q_e. Depending on the prices, the income in the year t is calculated as follows:

$$0.5 \cdot p_t^c \cdot q_c(\mathrm{BLG}_i) + p_t^e \cdot q_e(\mathrm{BLG}_i). \tag{9}$$

The associated costs of the production in the year t are:

$$p_t^b \cdot q_b(\mathrm{BLG}_i) + \frac{c^{\mathrm{oper}}(\mathrm{BLG}_i)}{(1+R)^t} + \frac{0.5 \cdot c^{\mathrm{trans}}(\mathrm{BLG}_i, \mathrm{d}) \cdot q_c(\mathrm{BLG}_i)}{(1+R)^t}. \tag{10}$$

where q_b denotes the additional biomass requirement needed for the CHP systems and c^{oper} is the yearly operational cost related to the production. We assume the fixed yearly transportation and storage costs (c^{trans}) for each unit of CO_2 captured given the transportation distance d. The transportation and the storage of the CO_2 is not performed by a pulp mill itself. Rather we consider the case of a pulp mill, which produces CO_2 and delivers to the border of the mill. This CO_2 is for sale to potential customers who will transport and store it. We assume that the pulp mill and customer share the profit from the CO_2 capture[8] equally, i.e., the mill owner receives one half of the profit from the capture of CO_2.

The difference of the terms (9) and (10) will be called the *operational profit* $p_t^{\mathrm{oper}}(\mathrm{BLG}_i)$. All these values, that is $q_c(.)$, $q_e(.)$, $q_b(.)$, $c^{\mathrm{oper}}(.)$, $c^{\mathrm{trans}}(., d)$, and d are input constants of the model. This means that given the price processes e_t, b_t, c_t the operational profit can be computed for each module BLG_i and each time point t.

Note that we will usually assume that $c^{\mathrm{oper}}(\mathrm{BLG}_i) = 4\% \cdot c^c(\mathrm{BLG}_i)$.

6.1.6 Discounting

When considering the time aspect of money, a discrete discount rate r will be used. The income and/or outcome will be expressed as: "time 0 money", i.e. , the value V at time t will be expressed as

$$\frac{V}{(1+r)^t}.$$

Note that discounting and learning are two independent notions. Learning means real decreasing of costs, while discounting is just projecting the same amount of money in time. The time 0 cost of investment c performed at time point t is therefore:

$$\frac{c}{(1+r)^t(1+R)^t},$$

that is, both effects apply.

6.1.7 Capital Investment Time

When the pulp mill owner invests in a module, it takes some time to build it (say 1–2 years). If we, in this paper, say that the pulp mill owner has invested in some module at time t (that is, $\mathbf{a}_t \in \vec{\mathcal{A}}_c$), it means that the module has been built in such a way that at time t it will be active for the first time.

[8] CO_2 profit = income for each unit of CO_2 sold – cost of transportation.

For example, if the pulp mill owner wants to operate module BLG_3 at time 10, we say that he/she has invested at time 10 while in reality it may take two years to build it and the decision has to be made at time 8. This makes no difference, as far we are aware of this situation, when interpreting the simulation results.

Technically, we accept the following special behavior: if the gasification period starts at time 10, the pulp mill owner wants to operate the module BLG_3 as the first module within this period (i.e. , at time 10), and the real build process takes, say, two years then the pulp mill owner in reality takes the decision at time 8, i.e. , already within the previous period. Moreover, if the pulp mill owner wants to operate module BLG_3 at time 1, in reality he/she must take the appropriate decision at time -1, i.e. , before simulation starts.

However, the question arises of discounting the capital investment cost. In this paper we use the discount factor corresponding to the year of the first activation of the module. For example, if the module BLG_3 with two years build-time should be active at time 10 (that is, in reality the pulp mill owner takes the decision at time 8), the corresponding capital investment cost is discounted with factor $1/(1+r)^{10}$ not $1/(1+r)^8$.

6.1.8 Account Balance of the Pulp Mill Owner

No doubt, the capital investment cost is relatively high for a single pulp mill owner. If the pulp mill owner wants to invest in a module with capital cost say $C_0 = 7$ MUSD at time 1, in reality he/she will probably not pay 7 MUSD directly at time 1. Instead, he/she will pay some fix amount C of money each of the next T_{retire} years so that when considering the discount factor r the amount paid will be the same, i.e. ,

$$\frac{C_0}{1+r} = C \sum_{t=1}^{T_{\mathrm{retire}}} \frac{1}{(1+r)^t}.$$

This is, in reality, important for healthy account balancing. On the other hand, the yearly cost C is computed precisely in such a way that the investment cost is equal to the amount that should be paid directly. If we are not interested in account balance (and we are not) there is no difference in paying the capital costs at once or paying a fixed yearly cost for the next T_{retire} years.

Therefore, in this paper the capital investment cost is paid fully at once as this is simpler for computations and estimations.

6.1.9 Special Case: The Last Period

The last gasification period is perhaps artificially ended prematurely by time horizon T. Hence, the capital investments meant for time T_{retire} could seem suboptimal for the shorter period. Therefore, within the last period all capital investment costs will be considered only with the fraction:

$$\frac{T - \mathbf{gp}(\#_{\mathbf{gp}}) + 1}{T_{\mathrm{retire}}}.$$

The last gasification period usually requires special treatment in computations.

6.1.10 Total Profit

Now, we define the total profit p achieved by a strategy $(\mathbf{gp}, \mathbf{a})$ in terms of "time–0 money". Denote the profit gained at time t by p_t. Then:

$$p = \sum_{t=1}^{T} \frac{p_t}{(1+r)^t}.$$

The profit gained at time t depends on operational profit achieved at time t and action taken at time t:

$$\begin{aligned} p_t &= p_t^{\text{oper}}(\mathbf{rs}(\mathbf{a}, t)) && \text{if } \mathbf{a}_t = \text{stay} \\ p_t &= p_t^{\text{oper}}(\mathbf{rs}(\mathbf{a}, t)) - \frac{c(\mathbf{a}_t)}{(1+R)^t} && \text{if } \mathbf{a}_t \in \vec{\mathcal{A}} \\ p_t &= p_t^{\text{oper}}(\mathbf{rs}(\mathbf{a}, t)) - \delta_t \frac{c(\mathbf{a}_t)}{(1+R)^t} && \text{if } \mathbf{a}_t \in \vec{\mathcal{A}}_c \end{aligned}$$

where

$$\delta_t = \begin{cases} \frac{T - \mathbf{gp}(\#_{\mathbf{gp}})+1}{T_{\text{retire}}} & \text{if } \mathbf{period\_end}(\mathbf{gp}, t) = T \\ 1 & \text{otherwise.} \end{cases}$$

6.1.11 Summary

For convenience the summary of notations used is shown in Table 12.

6.2 Assumptions

The following assumptions are made on input parameters of the model.

6.2.1 Costs

Costs should obey the following rules for any permutation (m_1, m_2, m_3) of modules BLG_1, BLG_2, and BLG_3.

$$c(m_1 \to m_2) \le c(m_2) \tag{11}$$
$$c(m_1 \to m_2) \le c(m_2 \setminus m_1 \mid m_1) \tag{12}$$
$$c(m_1 \to m_2) \le c(m_2 \setminus (m_1 \cup m_3) \mid m_1) \tag{13}$$
$$c(m_2 \setminus m_1 \mid m_1) \le c(m_2) \tag{14}$$
$$c(m_2 \setminus (m_1 \cup m_3) \mid m_1) \le c(m_2 \setminus m_1 \mid m_1). \tag{15}$$

(Note that assumptions (11) and (12) are actually dependent on (13–15) and are stated here only for clarity.) The above conditions claim that switching to an existing module is always cheaper than building it for the first time ((11), (12), and (13)) and that when building a new module, the existince of other modules cannot deteriorate the situation ((14), (15)).

6.2.2 Times

We assume that the horizon T is the integer multiple of retirement time T_{retire}.

Table 12: Notation summary.

c^c	...... capital cost
$\vec{c}$	...... switch-cost
c^{add}	...... additional switch-cost
c	...... cost in general
T	...... time horizon
T_{retire}	...... retirement time
r	...... discrete discount factor
p_t^e	...... electricity price at time t (not discounted yet)
p_t^b	...... biomass price at time t (not discounted yet)
p_t^e	...... CO_2 price at time t (not discounted yet)
p_t^{oper}	...... operational profit at time t (not discounted yet)
$\mathbf{period\_begin}(\mathbf{gp}, t)$	...... starting time of gasification period containing t
$\mathbf{period\_end}(\mathbf{gp}, t)$	...... ending time of gasification period containing t
$\mathcal{A}$	...... set of all possible actions
$\vec{\mathcal{A}}$	...... set of all possible switch-actions
$\vec{\mathcal{A}}_c$	...... set of all possible build-actions with “memory”
$\mathbf{a}$	...... vector of actions
$\mathbf{gp}$	...... gasification points
$\mathbf{rs}(\mathbf{a}, t)$	...... running strategy at time t
$(a)^{\mathbf{on}}$	...... module activated by the action a
$\mathbf{present}(a)$	...... modules assumed by the action a to be built earlier

6.2.3 Periods

We assume that the gasification periods are completely independent and hence can be independently optimized once gasification points $\mathbf{gp}$ are given.

6.3 Merging the Periods (Theorem 1)

Theorem 1. *Optimal strategy* $(\hat{\mathbf{gp}}, \hat{\mathbf{a}})$ *exists such that for each* $i = 1, \ldots, \#_{\hat{\mathbf{gp}}} - 2$

$$\hat{\mathbf{gp}}(i+2) - \hat{\mathbf{gp}}(i) > T_{\text{retire}}.$$

Proof. Let $(\hat{\mathbf{gp}}, \hat{a})$ be any optimal strategy and let $\hat{\mathbf{gp}}(i+2) - \hat{\mathbf{gp}}(i) \leq T_{\text{retire}}$ for some i. We construct a new optimal strategy $(\bar{\mathbf{gp}}, \bar{\mathbf{a}})$ having less pairs breaking the above condition.

The idea is to merge the i-th and the $(i+1)$-st gasification periods (denote them by P_i and P_{i+1}, respectively) into one period. This is feasible with respect to gasification points since $\hat{\mathbf{gp}}(i+2) - \hat{\mathbf{gp}}(i) \leq T_{\text{retire}}$. In other words, let:

$$\bar{\mathbf{gp}} = \hat{\mathbf{gp}}(1), \ldots, \hat{\mathbf{gp}}(i), \hat{\mathbf{gp}}(i+2), \ldots, \hat{\mathbf{gp}}(\#_{\hat{\mathbf{gp}}}).$$

On the other hand, we achieve the same running strategy (and hence the same operational profit). The actions $\bar{\mathbf{a}}_t$ will be the same as $\hat{\mathbf{a}}_t$ for all time-points except the points of P_{i+1}. In the latter period, we have to modify the actions since, e.g. , if one starts period P_{i+1} with command BLG_1 and module BLG_1 has been built within period P_i, then build-action BLG_1 is not valid after merging anymore — one should use switch to existing module BLG_1 instead.

Thus, we replace the original build-actions of P_{i+1} by respective switch-actions if the modules to be built already exist after merging. Similarly, we replace the original build-actions of P_{i+1} by respective modified build-actions if the set of already built modules changes after merging. The original switch-actions and action "stay" remain unchanged.

Nonetheless, according to assumptions (11)–(15) the modified actions are not more expensive than the original ones.[9] Hence merging of i-th and $(i+1)$-st period will not decrease the total profit. Therefore, $(\bar{\mathbf{gp}}, \bar{\mathbf{a}})$ is again an optimal strategy.

Corollary 1. *Optimal strategy* $(\hat{\mathbf{gp}}, \hat{\mathbf{a}})$ *exists having*

$$\#_{\hat{\mathbf{gp}}} \leq \frac{2T}{T_{\text{retire}}}.$$

Proof. Assume for the contrary that optimal strategy with minimum $\#_{\mathbf{gp}}$ fulfills:

$$\#_{\mathbf{gp}} \geq \frac{2T}{T_{\text{retire}}} + 1.$$

Take the gasification points $\mathbf{gp}(1), \mathbf{gp}(3), \ldots, \mathbf{gp}(2T/T_{\text{retire}} + 1)$. Should all of these points be distanced by more than T_{retire} then:

$$T - 1 \geq \mathbf{gp}\left(\frac{2T}{T_{\text{retire}}} + 1\right) - \mathbf{gp}(1) = \sum_{k=1}^{T/T_{\text{retire}}} \mathbf{gp}(2k+1) - \mathbf{gp}(2k-1) > \frac{T}{T_{\text{retire}}} T_{\text{retire}} = T,$$

[9] Actually, each cost must be considered with respect to learning. However, we do not shift the actions in time, therefore both the left- and right-hand sides of these inequalities will be "learned" by the same factor.

which is impossible. Therefore, there is such i that $\mathbf{gp}(2i+1) - \mathbf{gp}(2i-1) \le T_{\text{retire}}$. The $2i$-th and $(2i+1)$-st gasification periods can now be merged, similarly as in the proof of Theorem 1, thus producing the optimal strategy with less gasification points, a contradiction.

6.4 Estimating the Profit (Theorem 2)

Theorem 2. *Let* $(\hat{\mathbf{gp}}, \hat{\mathbf{a}})$ *be the optimal strategy. Let* $\hat{p}^{(i)}$ *denote its total profit on* i*-th gasification period* $\langle y_b, y_e\rangle$ $(i = 1, \ldots, \#_{\hat{\mathbf{gp}}})$ *stated as "time 0 money". Let* $C_{\text{cheapest}} = \min_i c^c(\text{BLG}_i)$ *be the initial capital investment cost for the cheapest of BLG modules. Then:*

$$\hat{p}^{(i)} \le \sum_{t=y_b}^{y_e} \frac{1}{(1+r)^t} \max_j \left(p_t^{\text{oper}}(\text{BLG}_j) - \delta^{(i)} \frac{c^c(\text{BLG}_j) - C_{\text{cheapest}}}{T_{\text{retire}}(1+R)^t} \right) - \frac{\delta^{(i)} C_{\text{cheapest}}}{(1+r)^{y_b}(1+R)^{y_b}}$$

where

$$\delta^{(i)} = \begin{cases} \frac{T - \mathbf{gp}(\#_{\mathbf{gp}})+1}{T_{\text{retire}}} & \text{if } i = \#_{\hat{\mathbf{gp}}} \\ 1 & \text{otherwise.} \end{cases}$$

The idea behind this estimation is the following: ignore the switch-costs. As for the running strategy, suppose that the most profitable module is running in each time point. However, for each year when the module is active, a corresponding capital investment cost must be paid (i.e. , the cost $c^c(.)/T_{\text{retire}}/(1+R)^t$). If, therefore, in this estimation the pulp mill owner uses the particular module for k years, he/she invests only the amount approximately proportional to k/T_{retire} while, in reality, he/she must invest the full capital investment cost regardless of whether he/she plans to use it for 1 or whole T_{retire} years. We, however, have to take discounting into consideration as well. One of the capital investments (at least the investment into the cheapest module) has to be realized in year y_b and hence appropriately discounted.

Proof. As defined,

$$\hat{p}^{(i)} = \sum_{t=y_b}^{y_e} \frac{1}{(1+r)^t} \Big(p_t^{\text{oper}}(\mathbf{rs}(\hat{\mathbf{a}}, t)) - \delta^{(i)} \frac{c(\hat{\mathbf{a}}_t)}{(1+R)^t} \Big).$$

When ignoring the switch costs we get:

$$\hat{p}^{(i)} \le \sum_{t=y_b}^{y_e} \frac{1}{(1+r)^t} \Big(p_t^{\text{oper}}(\mathbf{rs}(\hat{\mathbf{a}}, t)) - \delta^{(i)} \frac{c^c(\hat{\mathbf{a}}_t)}{(1+R)^t} I_{\{\hat{\mathbf{a}}_t \in \vec{\mathcal{A}}_c\}} \Big).$$

We now analyze the capital investment cost and limit it from below (which results in limiting the profit from above). Actually, each BLG part is bought at some time and then it is used for some years, perhaps even by activation of more modules. For example, a BLG part in $\text{BLG}_2 \cap \text{BLG}_3$ is always "active" when module BLG_2 or BLG_3 is on.

In order to simplify the terms re-denote the disjoint Venno-subsets of X_0 (see (1)) by $S_1, \ldots, S_7$, i.e. ,

$$X_0 = S_1 \cup \cdots \cup S_7.$$

Now the pulp mill owner invests in each of S_j at exactly one time-point within i-th gasification period (and this investment must be appropriately discounted and "learned") or he/she does not invest in that S_j at all. Actually, the pulp mill owner performs actions in $\mathcal{A}_c$ only; they can, however, be interpreted as investing in some of S_j sets. Therefore, for $j = 1, \ldots, 7$ we use the following discount factors:

$$d_j = \begin{cases} \frac{1}{(1+r)^t(1+R)^t} & \text{if the pulp-mill owner invest in } S_j \text{ at time } t \\ 0 & \text{if she does not invest in } S_j \text{ within } i\text{-th gasification period} \end{cases}$$

and

$$\sum_{t=y_b}^{y_e} \frac{\delta^{(i)}}{(1+r)^t(1+R)^t} c^c(\hat{\mathbf{a}}_t) I_{\{\hat{\mathbf{a}}_t \in \vec{\mathcal{A}}_c\}} = \delta^{(i)} \sum_{j=1}^{7} c^c(S_j) d_j.$$

The pulp mill owner invests in one of the modules (say, in module BLG_m) at time y_b. Hence,

$$S_j \subseteq \mathrm{BLG}_m \implies d_j = \frac{1}{(1+r)^{y_b}(1+R)^{y_b}}.$$

Now, let k_l ($l = 1, 2, 3$) be the number of points in time within i-th gasification period when module BLG_l is active. Obviously $k_1 + k_2 + k_3 = y_e - y_b + 1 \leq T_{\text{retire}}$ and, therefore,

$$\delta^{(i)} \sum_{j=1}^{7} c^c(S_j) d_j \geq \delta^{(i)} \sum_{j=1}^{7} c^c(S_j) \frac{1}{(1+r)^{y_b}(1+R)^{y_b}} I_{\{S_j \subseteq \mathrm{BLG}_m\}} +$$
$$+ \delta^{(i)} \sum_{j=1}^{7} c^c(S_j) \frac{d_j}{T_{\text{retire}}} \Big(k_1 I_{\{S_j \subseteq \mathrm{BLG}_1 \setminus \mathrm{BLG}_m\}} + k_2 I_{\{S_j \subseteq \mathrm{BLG}_2 \setminus \mathrm{BLG}_m\}} + k_3 I_{\{S_j \subseteq \mathrm{BLG}_3 \setminus \mathrm{BLG}_m\}} \Big).$$

In this sum, the capital investment cost of each part of BLG_m is considered fully, while all other BLG parts with the ratio of actually used years only. The right-hand side of this inequality can be restated as:

$$\delta^{(i)} \sum_{j=1}^{7} c^c(S_j) \frac{1}{(1+r)^{y_b}(1+R)^{y_b}} I_{\{S_j \subseteq \mathrm{BLG}_m\}} + \delta^{(i)} \sum_{j=1}^{7} c^c(S_j) \frac{d_j}{T_{\text{retire}}} \sum_{t=y_b}^{y_e} I_{\{S_j \subseteq \mathrm{BLG}_{\mathbf{rs}(\hat{\mathbf{a}},t)}\}} =$$
$$= \delta^{(i)} \sum_{j=1}^{7} c^c(S_j) \frac{1}{(1+r)^{y_b}(1+R)^{y_b}} I_{\{S_j \subseteq \mathrm{BLG}_m\}} + \delta^{(i)} \sum_{t=y_b}^{y_e} \sum_{j=1}^{7} c^c(S_j) \frac{d_j}{T_{\text{retire}}} I_{\{S_j \subseteq \mathrm{BLG}_{\mathbf{rs}(\hat{\mathbf{a}},t)}\}} =$$
$$= \frac{\delta^{(i)}}{(1+r)^{y_b}(1+R)^{y_b}} c^c(\mathrm{BLG}_m) + \delta^{(i)} \sum_{t=y_b}^{y_e} \frac{d_j}{T_{\text{retire}}} c^c(\mathrm{BLG}_{\mathbf{rs}(\hat{\mathbf{a}},t)} \setminus \mathrm{BLG}_m).$$

Since each module can be active only after it is completely built, it holds:

$$S_j \subseteq \mathrm{BLG}_{\mathbf{rs}(\hat{\mathbf{a}},t)} \implies d_j \geq \frac{1}{(1+r)^t(1+R)^t}.$$

Moreover,

$$c^c(\mathrm{BLG}_{\mathbf{rs}(\hat{\mathbf{a}},t)} \setminus \mathrm{BLG}_m) = c^c(\mathrm{BLG}_{\mathbf{rs}(\hat{\mathbf{a}},t)} \setminus (\mathrm{BLG}_m \cap \mathrm{BLG}_{\mathbf{rs}(\hat{\mathbf{a}},t)})) =$$
$$= c^c(\mathrm{BLG}_{\mathbf{rs}(\hat{\mathbf{a}},t)}) - c^c(\mathrm{BLG}_m \cap \mathrm{BLG}_{\mathbf{rs}(\hat{\mathbf{a}},t)})) \geq$$
$$\geq c^c(\mathrm{BLG}_{\mathbf{rs}(\hat{\mathbf{a}},t)}) - c^c(\mathrm{BLG}_m).$$

Therefore,

$$\frac{\delta^{(i)}}{(1+r)^{y_b}(1+R)^{y_b}} c^c(\mathrm{BLG}_m) + \delta^{(i)} \sum_{t=y_b}^{y_e} \frac{d_j}{T_{\mathrm{retire}}} c^c(\mathrm{BLG}_{\mathbf{rs}(\hat{\mathbf{a}},t)} \setminus \mathrm{BLG}_m) \geq$$
$$\geq \frac{\delta^{(i)}}{(1+r)^{y_b}(1+R)^{y_b}} c^c(\mathrm{BLG}_m) + \delta^{(i)} \sum_{t=y_b}^{y_e} \frac{c^c(\mathrm{BLG}_{\mathbf{rs}(\hat{\mathbf{a}},t)}) - c^c(\mathrm{BLG}_m)}{T_{\mathrm{retire}}(1+r)^t(1+R)^t}.$$

In this sum, the term $c^c(\mathrm{BLG}_m)$ is multiplied with the factor:

$$f = \delta^{(i)} \left(\frac{1}{(1+r)^{y_b}(1+R)^{y_b}} - \sum_{t=y_b}^{y_e} \frac{1}{T_{\mathrm{retire}}(1+r)^t(1+R)^t} \right).$$

However, since $t \geq y_b$,

$$f \geq \delta^{(i)} \left(\frac{1}{(1+r)^{y_b}(1+R)^{y_b}} - \sum_{t=y_b}^{y_e} \frac{1}{T_{\mathrm{retire}}(1+r)^{y_b}(1+R)^{y_b}} \right) =$$
$$= \delta^{(i)} \left(\frac{1}{(1+r)^{y_b}(1+R)^{y_b}} - \frac{y_e - y_b + 1}{T_{\mathrm{retire}}(1+r)^{y_b}(1+R)^{y_b}} \right) \geq$$
$$\geq \delta^{(i)} \left(\frac{1}{(1+r)^{y_b}(1+R)^{y_b}} - \frac{1}{(1+r)^{y_b}(1+R)^{y_b}} \right) = 0$$

as $y_b - y_e + 1 \leq T_{\mathrm{retire}}$. Hence $f \cdot c^c(\mathrm{BLG}_m) \geq f \cdot C_{\mathrm{cheapest}}$, since $c^c(\mathrm{BLG}_m) \geq C_{\mathrm{cheapest}}$. We then get the following lower bound for capital investment cost:

$$\sum_{t=y_b}^{y_e} \frac{\delta^{(i)}}{(1+r)^t(1+R)^t} c^c(\hat{\mathbf{a}}_t) I_{\{\hat{\mathbf{a}}_t \in \vec{\mathcal{A}}_c\}} \geq$$
$$\geq \delta^{(i)} \frac{C_{\mathrm{cheapest}}}{(1+r)^{y_b}(1+R)^{y_b}} + \delta^{(i)} \sum_{t=y_b}^{y_e} \frac{1}{T_{\mathrm{retire}}(1+r)^t(1+R)^t} \left(c^c(\mathrm{BLG}_{\mathbf{rs}(\hat{\mathbf{a}},t)}) - C_{\mathrm{cheapest}} \right).$$

So far we have, therefore, obtained the estimation:

$$\hat{p}^{(i)} \leq \sum_{t=y_b}^{y_e} \frac{1}{(1+r)^t} \left(p_t^{\mathrm{oper}}(\mathbf{rs}(\hat{\mathbf{a}},t)) - \delta^{(i)} \frac{c^c(\hat{\mathbf{a}}_t)}{(1+R)^t} I_{\{\hat{\mathbf{a}}_t \in \vec{\mathcal{A}}_c\}} \right) \leq$$
$$\leq \sum_{t=y_b}^{y_e} \frac{1}{(1+r)^t} \left(p_t^{\mathrm{oper}}(\mathbf{rs}(\hat{\mathbf{a}},t)) - \delta^{(i)} \frac{c^c(\mathrm{BLG}_{\mathbf{rs}(\hat{\mathbf{a}},t)}) - C_{\mathrm{cheapest}}}{T_{\mathrm{retire}}(1+R)^t} \right) - \delta^{(i)} \frac{C_{\mathrm{cheapest}}}{(1+r)^{y_b}(1+R)^{y_b}}.$$

As we do not now the value $\mathbf{rs}(\hat{\mathbf{a}},t)$, i.e. , we do not know which module is on at time t, we simply take the maximum over all modules BLG_1, BLG_2, and BLG_3. The statement of the theorem:

$$\hat{p}^{(i)} \leq \sum_{t=y_b}^{y_e} \frac{1}{(1+r)^t} \max_j \left(p_t^{\mathrm{oper}}(\mathrm{BLG}_j) - \delta^{(i)} \frac{c^c(\mathrm{BLG}_j) - C_{\mathrm{cheapest}}}{T_{\mathrm{retire}}(1+R)^t} \right) - \frac{\delta^{(i)} C_{\mathrm{cheapest}}}{(1+r)^{y_b}(1+R)^{y_b}}$$

follows.

Summing the estimation in Theorem 2 by i we estimate the optimal profit $\hat{p}$ by:

$$\hat{p} = \sum_{i=1}^{\#_{\hat{\mathbf{gp}}}} \hat{p}^{(i)} \leq \sum_{t=1}^{T} \frac{1}{(1+r)^t} \max_j \left(p_t^{\mathrm{oper}}(\mathrm{BLG}_j) - \delta_t \frac{c^c(\mathrm{BLG}_j) - C_{\mathrm{cheapest}}}{T_{\mathrm{retire}}(1+R)^t} \right) -$$
$$- C_{\mathrm{cheapest}} \left(\frac{1}{(1+r)^{\hat{\mathbf{gp}}(1)}(1+R)^{\hat{\mathbf{gp}}(1)}} + \cdots + \frac{1}{(1+r)^{\hat{\mathbf{gp}}(\#_{\hat{\mathbf{gp}}}-1)}(1+R)^{\hat{\mathbf{gp}}(\#_{\hat{\mathbf{gp}}}-1)}} + \right. \tag{16}$$
$$\left. + \frac{T - \hat{\mathbf{gp}}(\#_{\hat{\mathbf{gp}}}) + 1}{T_{\mathrm{retire}}} \frac{1}{(1+r)^{\hat{\mathbf{gp}}(\#_{\hat{\mathbf{gp}}})}(1+R)^{\hat{\mathbf{gp}}(\#_{\hat{\mathbf{gp}}})}} \right)$$

where

$$\delta_t = \begin{cases} \frac{T - \hat{\mathbf{gp}}(\#_{\hat{\mathbf{gp}}}) + 1}{T_{\mathrm{retire}}} & \text{if } \mathbf{period\_end}(\hat{\mathbf{gp}}, t) = T \\ 1 & \text{otherwise.} \end{cases}$$

This term does not depend on $\hat{\mathbf{a}}$ at all. It depends on $\hat{\mathbf{gp}}$ only.

For $\#_{\hat{\mathbf{gp}}} = 3$ and $T/T_{\mathrm{retire}} = 2$ the right-hand side of (16) maximizes at:

$$\begin{aligned} \mathbf{gp}(1) &= 1 \\ \mathbf{gp}(2) &= T_{\mathrm{retire}} + 1 \\ \mathbf{gp}(3) &= T \end{aligned}$$

and for $\#_{\hat{\mathbf{gp}}} = 4$, $T/T_{\mathrm{retire}} = 2$ at:

$$\begin{aligned} \mathbf{gp}(1) &= 1 \\ \mathbf{gp}(2) &= T_{\mathrm{retire}} + 1 \\ \mathbf{gp}(3) &= T - 1 \\ \mathbf{gp}(4) &= T. \end{aligned}$$

Denote for the special case of $T/T_{\mathrm{retire}} = 2$ these maximized terms by p_3 and p_4, respectively. In particular, let:

$$p_3 = \sum_{t=1}^{T} \frac{1}{(1+r)^t} \max_j \left(p_t^{\mathrm{oper}}(\mathrm{BLG}_j) - \delta_t \frac{c^c(\mathrm{BLG}_j) - C_{\mathrm{cheapest}}}{T_{\mathrm{retire}}(1+R)^t} \right) -$$
$$- C_{\mathrm{cheapest}} \left(\frac{1}{(1+r)(1+R)} + \frac{1}{\big((1+r)(1+R)\big)^{T_{\mathrm{retire}}+1}} + \right. \tag{17}$$
$$\left. + \frac{1}{T_{\mathrm{retire}}\big((1+r)(1+R)\big)^{T}} \right);$$

$$p_4 = \sum_{t=1}^{T} \frac{1}{(1+r)^t} \max_j \left(p_t^{\mathrm{oper}}(\mathrm{BLG}_j) - \delta_t \frac{c^c(\mathrm{BLG}_j) - C_{\mathrm{cheapest}}}{T_{\mathrm{retire}}(1+R)^t} \right) -$$
$$- C_{\mathrm{cheapest}} \left(\frac{1}{(1+r)(1+R)} + \frac{1}{\big((1+r)(1+R)\big)^{T_{\mathrm{retire}}+1}} + \right. \tag{18}$$
$$\left. + \frac{1}{\big((1+r)(1+R)\big)^{T-1}} + \frac{1}{T_{\mathrm{retire}}\big((1+r)(1+R)\big)^{T}} \right).$$

Corollary 2. *Let $T/T_{\text{retire}} = 2$ and let p_k $(k = 3, 4)$ be constants given by (17) and (18). Let $(\hat{\mathbf{gp}}, \hat{\mathbf{a}})$ be an optimal strategy. Let a feasible strategy $(\bar{\mathbf{gp}}, \bar{\mathbf{a}})$ exist with $\#_{\bar{\mathbf{gp}}} \leq k-1$ having total profit $\bar{p} > p_k$. Then $\#_{\hat{\mathbf{gp}}} \leq k-1$.*

Proof. Should $\#_{\hat{\mathbf{gp}}} \geq k$ for some optimal strategy $(\hat{\mathbf{gp}}, \hat{\mathbf{a}})$, then for its total profit $\hat{p}$ it holds $\hat{p} \leq p_k$. Therefore,

$$p_k < \bar{p} \leq \hat{p} \leq p_k$$

is a contradiction.

6.5 Eliminating the Switch-Choices (Theorem 3)

Recall that the gasification periods are independent. Therefore, to find the optimal series of actions given the gasification points actually means to find optimal series of actions for each of the gasification periods. Moreover, the gasification periods can be optimized separately.

Suppose in this section the the capital investment actions have been fully distributed over the period $\langle y_b, y_e \rangle$, that is, the decision on which modules to build and when to build them has already been taken. The only decision that remains is to determine the actual running strategy, that is, to distribute the switch actions: optimally and feasibly with respect to the capital investment actions.

There are, of course, many feasible distributions and we can, however, prove for some of them that they are suboptimal.

Theorem 3. *Let $\langle y_b, y_e \rangle$ be a gasification period. Let $\mathbf{a}$ be a feasible series of actions on $\langle y_b, y_e \rangle$. Let $\tau \in \{y_b, \ldots, y_e\}$ denote the point in time such that $\mathbf{a}_\tau \in \vec{\mathcal{A}} \cup \mathcal{A}_c$ and this action changes the running strategy from module BLG_i to BLG_j.*

(a) if $\tau > y_b$, $\mathbf{a}_{\tau-1} = \text{stay}$ and

$$p^{\text{oper}}_{\tau-1}(\mathrm{BLG}_i) < p^{\text{oper}}_{\tau-1}(\mathrm{BLG}_j) - \frac{r + R + rR}{(1+r)} \cdot \frac{c(\mathbf{a}_\tau)}{(1+R)^\tau}$$

then $\mathbf{a}$ is suboptimal.

(b) if $\tau < y_e$, $\mathbf{a}_{\tau+1} = \text{stay}$ and

$$p^{\text{oper}}_{\tau}(\mathrm{BLG}_j) < p^{\text{oper}}_{\tau}(\mathrm{BLG}_i) + \frac{r + R + rR}{(1+r)(1+R)} \cdot \frac{c(\mathbf{a}_\tau)}{(1+R)^\tau}$$

then $\mathbf{a}$ is suboptimal.

The primary aim of this theorem (as the section heading states) is to eliminate the switch-choices, i.e. , the case when $\mathbf{a}_\tau \in \vec{\mathcal{A}}$. It is, however, valid (and can be used) for capital investment actions ($\mathbf{a}_\tau \in \mathcal{A}_c$) as well.

Proof. We prove only part (a) — the proof of part (b) is similar. As for part (a) we can transform the series of actions $\mathbf{a}$ into a new feasible series $\bar{\mathbf{a}}$ as follows:

$$\bar{\mathbf{a}}_t = \begin{cases} \mathbf{a}_\tau & \text{if } t = \tau - 1 \\ \mathbf{a}_{\tau-1} = \text{stay} & \text{if } t = \tau \\ \mathbf{a}_t & \text{otherwise} \end{cases}$$

that is, we swap actions at time τ and $\tau - 1$. In particular, we perform the action $\mathbf{a}_\tau$ one year earlier in $\bar{\mathbf{a}}$ than in $\mathbf{a}$. With this change, the profit changes as well. Since no points in time except τ and $\tau - 1$ have been changed, the profit difference of series $\mathbf{a}$ and $\bar{\mathbf{a}}$ stated as "time $\tau - 1$ money" is:

$$\begin{aligned} d = &\left(p^{\text{oper}}_{\tau-1}(\text{BLG}_i) + \frac{p^{\text{oper}}_{\tau}(\text{BLG}_j)}{1+r} - \frac{c(\mathbf{a}_\tau)}{(1+r)(1+R)^\tau} \right) - \\ &- \left(p^{\text{oper}}_{\tau-1}(\text{BLG}_j) + \frac{p^{\text{oper}}_{\tau}(\text{BLG}_j)}{1+r} - \frac{c(\mathbf{a}_\tau)}{(1+R)^{\tau-1}} \right) = \\ &= p^{\text{oper}}_{\tau-1}(\text{BLG}_i) - \left(p^{\text{oper}}_{\tau-1}(\text{BLG}_j) - \frac{r+R+rR}{(1+r)} \cdot \frac{c(\mathbf{a}_\tau)}{(1+R)^\tau} \right). \end{aligned}$$

Therefore, if $d < 0$ the series of actions $\mathbf{a}$ is suboptimal, as the theorem claims.

6.6 Propagating the Substrategies (Theorem 4)

In this section we state how to spread the information gathered by optimizing one gasification period and, hence, easily optimize another gasification period.

Theorem 4. *Let $y_b \leq y_e \leq T - 2$, let $\hat{\mathbf{a}}$ be the optimal series of actions for period $\langle y_b, y_e\rangle$ and $\hat{p}$ be the optimal profit achieved on period $\langle y_b, y_e\rangle$. Then, for maximum profit $\hat{p}^+$ on period $\langle y_b, y_e + 1\rangle$ it holds:*

$$\hat{p}^+ \leq \hat{p} + \max_j \left(p^{\text{oper}}_{y_e+1}(\text{BLG}_j) \right).$$

Moreover, if $p^{\text{oper}}_{y_e+1}(\mathbf{rs}(\hat{\mathbf{a}}, y_e)) = \max_j \left(p^{\text{oper}}_{y_e+1}(\text{BLG}_j) \right)$ then

$$\hat{p}^+ = \hat{p} + p^{\text{oper}}_{y_e+1}(\mathbf{rs}(\hat{\mathbf{a}}, y_e))$$

and this profit is achieved by series of actions $\mathbf{a}^+$:

$$\bar{\mathbf{a}}^+_t = \begin{cases} \hat{\mathbf{a}}_t & t \in \{y_b, \dots, y_e\} \\ \text{stay} & t = y_e + 1. \end{cases}$$

Proof. Let $\hat{\mathbf{a}}^+$ be the optimal series of actions for period $\langle y_b, y_e + 1\rangle$ and $\hat{p}^+$ be its profit. Then, the series of actions $\bar{\mathbf{a}}$

$$\bar{\mathbf{a}}_t = \hat{\mathbf{a}}^+_t$$

for $t \in \{y_b, \dots, y_e\}$ is feasible for period $\langle y_b, y_e\rangle$ and achieves profit:

$$\bar{p} = \hat{p}^+ - p^{\text{oper}}_{y_e+1}(\mathbf{rs}(\hat{\mathbf{a}}^+, y_e)) + \frac{c(\hat{\mathbf{a}}^+_{y_e+1})}{(1+r)^{y_e+1}(1+R)^{y_e+1}} \tag{19}$$

Note that as $y_e \leq T-2$, both $y_e, y_e+1 \leq T-1$, thus none of the periods $\langle y_b, y_e\rangle$, $\langle y_b, y_e+1\rangle$ is the last period. This is important since within the last period the capital costs are not covered fully but only with a ratio proportional to the period length. Hence, we are not able to handle the last period with this reasoning. However, as $y_e \leq T - 2$, this is not the case and the equation (19) holds.

Since $\bar{\mathbf{a}}$ is the feasible series of actions, it holds $\bar{p} \leq \hat{p}$, i.e. ,

$$\hat{p}^+ \leq \hat{p} + p^{\text{oper}}_{y_e+1}(\mathbf{rs}(\hat{\mathbf{a}}^+, y_e)) - \frac{c(\hat{\mathbf{a}}^+_{y_e+1})}{(1+r)^{y_e+1}(1+R)^{y_e+1}} \leq \hat{p} + \max_j \left(p^{\text{oper}}_{y_e+1}(\text{BLG}_j)\right) \tag{20}$$

as the theorem claims. Moreover, the series of actions:

$$\bar{\mathbf{a}}^+_t = \begin{cases} \hat{\mathbf{a}}_t & t \in \{y_b, \ldots, y_e\} \\ \text{stay} & t = y_e + 1 \end{cases}$$

is feasible for the period $\langle y_b, y_e + 1 \rangle$. Its profit is:

$$\hat{p} + p^{\text{oper}}_{y_e+1}(\mathbf{rs}(\hat{\mathbf{a}}, y_e)).$$

Therefore,

$$\hat{p} + p^{\text{oper}}_{y_e+1}(\mathbf{rs}(\hat{\mathbf{a}}, y_e)) \leq \hat{p}^+. \tag{21}$$

If $p^{\text{oper}}_{y_e+1}(\mathbf{rs}(\hat{\mathbf{a}}, y_e)) = \max_j \left(p^{\text{oper}}_{y_e}(\text{BLG}_j)\right)$, from (20) and (21) we get:

$$\hat{p} + p^{\text{oper}}_{y_e+1}(\mathbf{rs}(\hat{\mathbf{a}}, y_e)) \leq \hat{p}^+ \leq \hat{p} + p^{\text{oper}}_{y_e+1}(\mathbf{rs}(\hat{\mathbf{a}}, y_e)).$$

Therefore, equality holds, i.e. , the series of actions $\bar{\mathbf{a}}^+$ is optimal for the period $\langle y_b, y_e + 1\rangle$ and gains profit

$$\hat{p}^+ = \hat{p} + p^{\text{oper}}_{y_e+1}(\mathbf{rs}(\hat{\mathbf{a}}, y_e)).$$

7 Generating the Price Processes

Price information was taken from Riahi *et al.* (2004) and Nakicenovic and Riahi (2002). Riahi et al. (2004) computed electricity and carbon prices as shadow prices in GHG stabilization runs including carbon capture technologies (CCT) aiming at atmospheric CO_2 concentrations at about 550 ppmv. Two stabilization scenarios for each baseline were developed — one assuming constant costs for CCTs (A2–550s, B2–550s), and one including learning for CCTs (A2–550t, B2–550t). All four stabilization scenarios are based on iterated runs of MESSAGE-MACRO (Messner and Schrattenholzer, 2000). The MESSAGE-MACRO is a "frictionless" global optimization framework assuming full spatial and temporal flexibility, including the free movement of investments. The resulting CO_2 emissions trajectories of the mitigation scenarios are shown in Figure 4. Emissions peak at about 9 to 12 GtC around 2050. Emissions decline to slightly less than the 1990 emissions level (6 GtC) by 2100. These emissions profiles are similar to other emissions trajectories for 550 ppmv stabilization cases found in the literature (Wigley *et al.*, 1996; Riahi and Roehrl, 2000).

7.1 CO_2 Price

The carbon value is an endogenous output calculated by the MESSAGE model. It can be interpreted either as a carbon tax or value of an emission permit that has to be introduced in a carbon-constrained world in order to meet the stabilization target. In the stabilization scenarios, CO_2 prices grow steadily from about 5 US\$/tCO_2 in 2020, to about 7–17

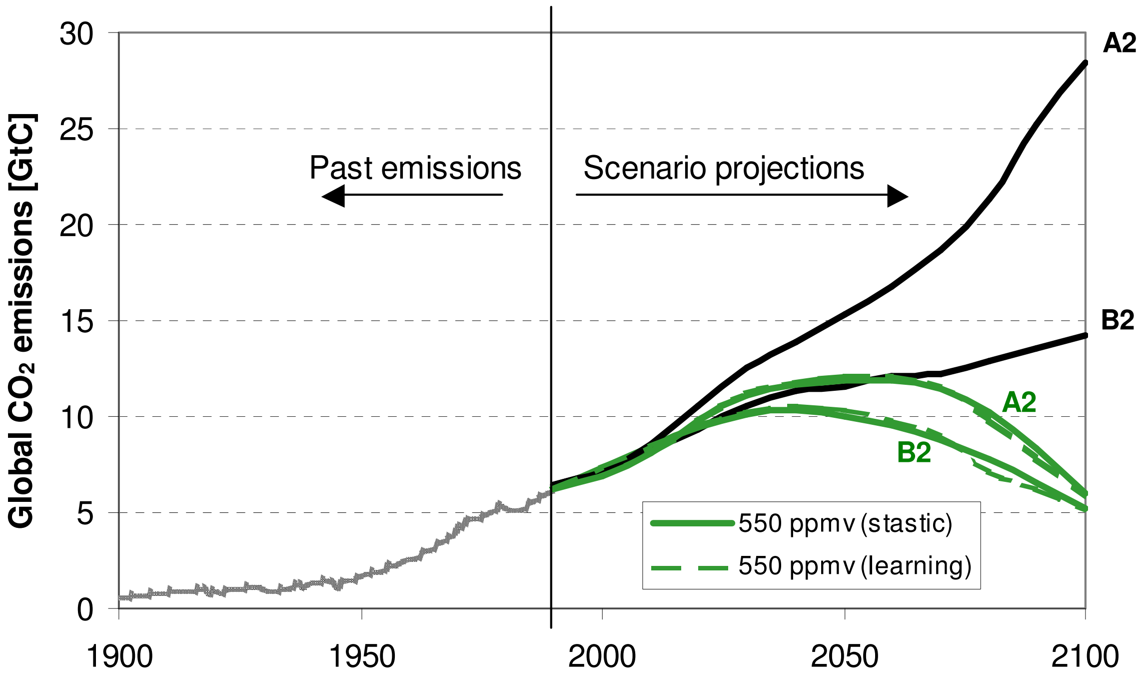


Figure 4: CO_2 emission trajectories.

US$/t$CO_2$ in 2050, to about 33–70 US$/t$CO_2$ in 2070, and to about 110–136 US$/t$CO_2$ in 2100. The sharp increase at the end of the century is partly due to discounting with a 5% annual rate. In order to constrain the range within which the prices are allowed to fluctuate, we selected the A2–550t price trajectory as an approximation of the upper bound and the B2–550t price trajectory as an approximation of the lower bound. Mainly due to discounting and also due to population and GDP growth, the CO_2 price process is modelled to be time dependent. More precisely, the CO_2 price trajectories are generated as follows:

$$p_t^c = c_1 + c_2 t + c_3 t^2 + \epsilon_t^c \tag{22}$$

where $\epsilon_t^c \sim N(0, (\sigma_t^c)^2)$ and $(\sigma_t^c)^2 = s_0^c + s_1^c t^2$. The parameters c_i, $i = 1, 2, 3$ were estimated to fit the carbon shadow prices by Riahi *et al.* (2004) as described above. ϵ_t^c were conjectured based on subjective judgment. Figure 5 shows the CO_2 price trajectories produced by equation (22) for 10 simulations.

7.2 Electricity Price

Due to the stabilization constraint, Riahi *et al.* (2004) compute an electricity price increase of about 100% of the coming century. We fitted the electricity price trajectory to the following equation:

$$p_t^e = e_1 + e_2 t + e_3 t^2 + \epsilon_t^e \tag{23}$$

where $\epsilon_t^e \sim N(0, \sigma_e^2)$. The electricity price is modelled as a time dependent process. The parameters e_i, $i = 1, 2, 3$ were estimated to fit the electricity shadow prices by Riahi *et al.* (2004). ϵ_t^e and the correlation between the CO_2 and the electricity price, $\rho_(p^c, p^e)$, were

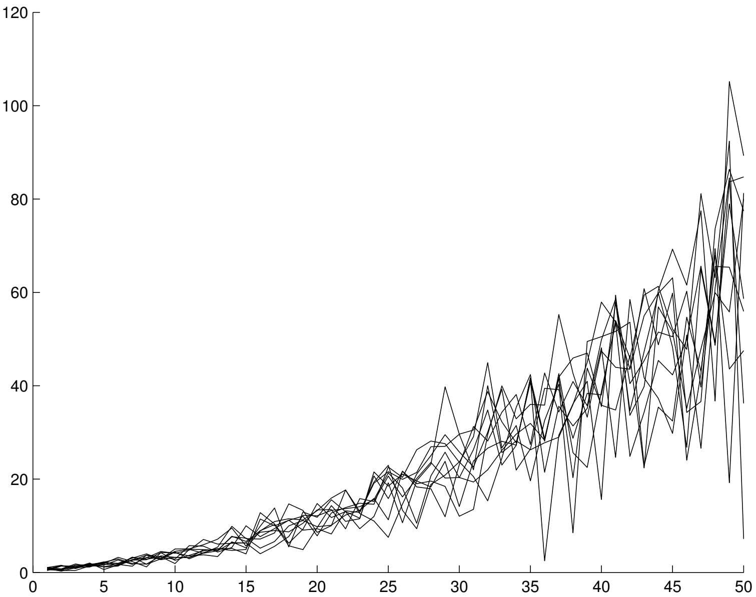


Figure 5: CO_2 prices trajectories produced by 10 simulations.

conjectured based on subjective judgment. Figure 6 shows the electricity price trajectories produced by equation (23) for 10 simulations.

7.3 Biomass Price

In a comparative study of energy scenarios Nakicenovic and Riahi (2002) compute, using the MESSAGE-MACRO modeling framework, shadow prices for inter alia biomass for energy — essentially representing marginal costs given the scenario assumptions. We again selected the values for the A2 and the B2 scenario in order to guarantee overall consistency with the MESSAGE-MACRO modeling framework. The price development is estimated consistent with historical trends of wood prices compared to pulp wood price statistics (FAO, 2003). The biomass prices are generated as:

$$p_t^b = b_1 + b_2 t + b_3 t^2 + \epsilon_t^b \tag{24}$$

where $\epsilon_t^b \sim N(0, (\sigma_t^b)^2)$ and $(\sigma_t^b)^2 = s_0^b e^{s_1^b t}$. Similarly to the electricity price and the CO_2 price also the biomass price is modelled as a time dependent process. It is assumed that cost reductions in forest operation and harvesting are not entirely offset by the increase in price due to increased demand. The parameters b_i, $i = 1, 2, 3$ were estimated to fit the biomass shadow prices by Riahi *et al.* (2004). ϵ_t^b and the correlation between the CO_2 price and the biomass price, ρ_{p^c,p^b}, were conjectured based on subjective judgment. Figure 7 shows the biomass price trajectories produced by equation (24) for 10 simulations.

8 The Algorithm

We now discuss the algorithm used to optimize the pulp mill owner decision.

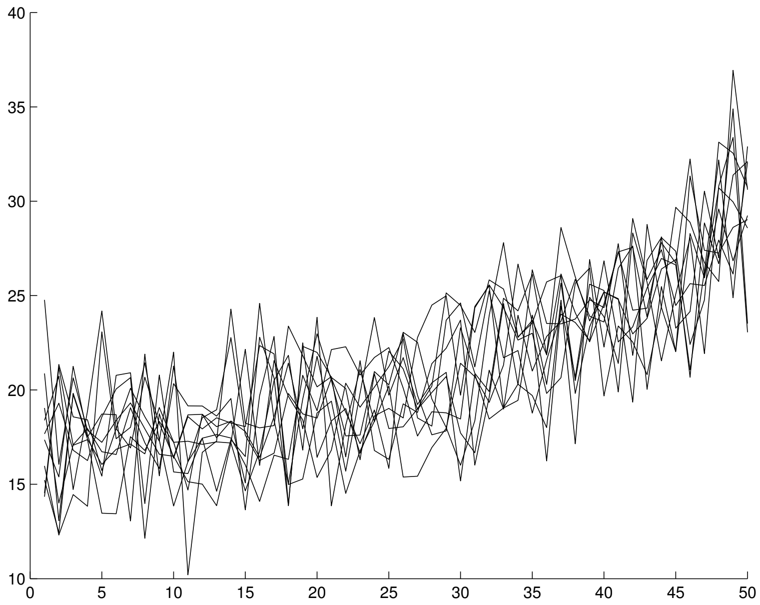


Figure 6: Electricity prices trajectories produced by 10 simulations.

First of all, realize that it is improbable (although possible) that the pulp mill owner ends some gasification period prematurely as his/her optimal action. If he/she does this, say one year earlier than time T_{retire} expires and ceteris paribus, at least some capital investment action will be performed one year earlier. Because of discounting and learning, instead of the cost c he/she then pays the cost $(1+r)(1+R)c$, that is, the difference will be approximately $(r+R)c$. As an advantage, he/she wins the chance to choose the effective module for time point T_{retire}. Therefore, profit is decreased by approximately $(r+R)c$ for some capital investment cost c and increased by the difference of operational profits for some two modules.[10] However, the stated difference in costs is within "real-world" parameter values probably higher than the stated difference in profits. For $T_{\text{retire}} = 25$ and $T = 50$ (that is, for our case), therefore, probably the optimal gasification points are $(1, 25, 50)$.

Our algorithm is optimized for this case, however, it does not ignore the (improbable) case that another choice should optimally be taken. Therefore, our algorithm is fast for "reasonable" input parameters as it checks the case $(1, 25, 50)$ and uses the estimations (which is once again fast to compute) to prove that other choices are suboptimal. For "non-reasonable" input parameters such an algorithm can be very slow (in an extreme case the full exponential search will be performed).

We now start with a rough skeleton of the algorithm and later refine each of its steps. The basic idea of the simulation is very simple; we check all feasible strategies and select

[10]This consideration is only approximate as the following has not been discussed:

- switching costs and additional (switching) cost paid by capital investment actions, and
- at each time point only one action can be taken, hence, shifting the actions over time need not always be plausible.

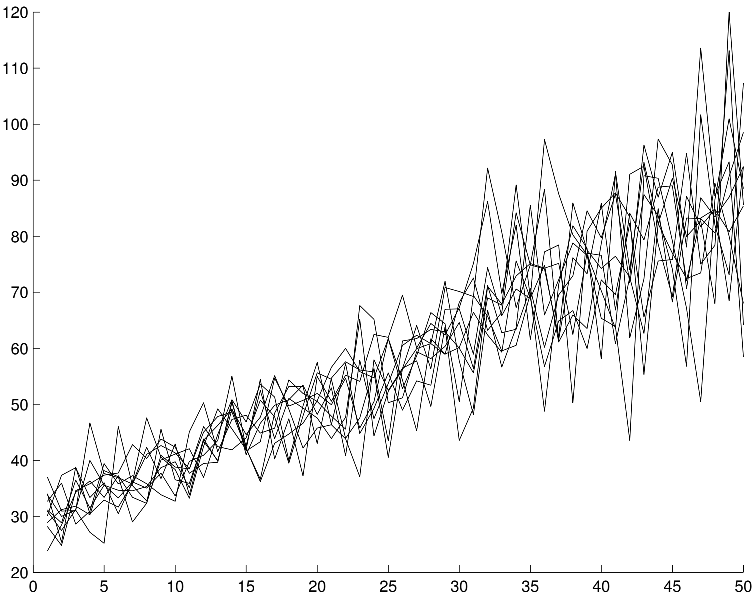


Figure 7: Biomass prices trajectories produced by 10 simulations.

the one with maximum profit achieved. Such an algorithm would be obviously correct but unacceptable with respect to computation time.

This is where theorems of this paper are used — they prove (under some circumstances) that some relatively large amount of feasible strategies must be suboptimal. With this help the number of strategies that have to be checked is significantly decreased and the simulation stops in effective time. It is, however, true that the eliminating effect of the theorems depends on the input parameters of the algorithm. Should the input values significantly change it is possible that achieved computation time will still be too high — the theorems have been carefully chosen in such a way that they result in an algorithm with good performance for the input parameters observed in a real world.

Although we only "check all feasible strategies", such a check must be well organized because for the eliminating effect of theorems it is important to find better strategies earlier (the worse strategies are then earlier recognized as such and, hence, a larger number of strategies can be suppressed). We expect that "better strategies" will use only few gasification periods, will not build too many modules within a period and will not switch too often.

Thus, the corresponding strategy search will be organized as follows (the algorithm is schematically stated in Figure 8):

1. First of all, we choose the number of gasification points ($\#_{\mathbf{gp}}$) our strategy will use, starting with T/T_{retire} (i.e. , with T_{retire}-years periods) and ending with T (i.e. , with 1-year periods). Thus, we prefer less periods which are, as a result, longer.

2. For the chosen $\#_{\mathbf{gp}}$ we check all feasible gasification points (see (2)). This splits the time scale $\{1, \ldots, T\}$ into gasification periods.

3. Each of the gasification periods will now be optimized separately (the total profit is given by the appropriately discounted sum of period profits).

4. We start the period optimization by choosing the number of modules built within the particular period (1–3), preferring less modules.

5. Now, we choose which modules will be built (cheaper modules are preferred) and when exactly they will be built in order not to violate feasibility (see (3)–(8)), e.g. , some module must be built at the beginning of each period.

6. It suffices now to add switch actions by back-tracking through all of the possibilities. We prefer not to switch as the first choice at each point in time.

1. **for** each $\#_{\mathbf{gp}} := T/T_{\text{retire}}$ **to** T **do**
2. **for** each feasible **gp** of size $\#_{\mathbf{gp}}$ **do**
3.   **for** each gasification period $\langle y_b, y_e \rangle$ defined by **gp do**
4.   **for** each $\#_{\text{BLG}} := 1$ to 3 **do**
5.   **for** each subset K of $\{\text{BLG}_1, \text{BLG}_2, \text{BLG}_3\}$ of size $\#_{\text{BLG}}$ **do**
6.   **for** each feasible distribution of capital investment actions for modules in K within $\langle y_b, y_e \rangle$ **do**
7.   **for** each feasible distribution of switch actions for modules in S within $\langle y_b, y_e \rangle$ **do**
8.   **compute** the strategy profit;
9. **return** the best profit found;

Figure 8: Basic skeleton of the algorithm.

Now we are ready to apply theorems. First of all, observe that within the optimization process we possibly multiply optimize the same gasification period. For example, if the gasification points are $(1, 10, 30)$ we have to optimize the period $\langle 1, 10 \rangle$ and when the gasification points are $(1, 10, 31)$ we again optimize the same period $\langle 1, 10 \rangle$. However, as gasification periods are independent, the optimal strategy for $\langle 1, 10 \rangle$ must in both cases be the same as well. Hence, it is reasonable to maintain the cache (the knowledge base) of all optimal strategies for gasification periods found so far. The optimization is started only if the required strategy is not available in cache, otherwise the strategy is directly read from the cache. Of course, after optimal strategy for some gasification period is found, it is stored in cache for (possible) future use. Moreover, always when we store some optimal period strategy in cache, we apply Theorem 4 as we can possibly store the optimal strategy for the extended period as well.

The actual refinements are as follows:

- Consult the algorithm in Figure 8. According to Corollary 1 the upper bound for $\#_{\mathbf{gp}}$ in Step 1 of the algorithm can be justified to $2T/T_{\text{retire}}$ instead of T. This is at most 4 for $T/T_{\text{retire}} = 2$.

  Moreover, this bound can be made yet tighter using Corollary 2. If we have found a feasible strategy with profit p and $\#_{\mathbf{gp}} = 2$ where $p > \hat{p}_3$ in notation of Corollary 2, then it is not necessary to check strategies with $\#_{\mathbf{gp}} = 3, 4$ anymore. Similarly, if we have found a feasible strategy with profit p and $\#_{\mathbf{gp}} = 3$ where $p > \hat{p}_4$, then it is not necessary to check strategies with $\#_{\mathbf{gp}} = 4$ anymore.

- So far, we have improved the Step 1 of the algorithm. Theorem 1 improves Step 2 — we are not interested in all possible gasification points, we need to deal only with those strategies where the gasification points fulfill the condition of Theorem 1.

- Further algorithm improvements can be achieved by using estimations. Before the algorithm proceeds to Step 3, it estimates the maximum profit achievable at given gasification points. Note that in Step 3 the gasification points (and hence the periods) are already chosen (this happened in Step 2), hence we can estimate from above the profit achievable at each of the gasification periods, sum up and get the upper estimation of the profit achievable within chosen gasification points. If this estimation is worse than the best strategy found so far we will not proceed in optimizing the periods, we instead directly proceed to the next gasification points choice, thus omitting Step 3 or the rest. Note that the estimation should be done again and again in each iteration of Step 3 even for the same gasification points, because as the algorithm proceeds, the knowledge-base (i.e. , the cache) extends and thus tighter estimations are possible as time passes (the situation that was not rejected earlier can be rejected now, when the knowledge base has been extended).

  The profit estimation for the period itself is done using Theorem 2. Moreover, under some circumstances (according to the content of the knowledge base) the estimation in Theorem 4 can apply. If this is the case, the tighter of both estimations is used. Of course, if there are data in cache for a particular period, no estimation is necessary, we use the exact optimal period profit read from the cache instead.

- We will not refine Steps 4–6 of the algorithm as there are not so many possibilities when compared to the other steps.

- However, we must improve the performance of Step 7. As we expect that periods are long (i.e. , approx. T_{retire}) and at most three years are already endowed with action (i.e. , the capital investment action) all other points in time (which are many) are free for a switch action. Actually, at each point in time the pulp mill owner can switch to any module that has already been built. Finally, the module that is on can even influence the capital investment cost.

  We, therefore, proceed in a left-to-right manner in time, always testing all possible switches. We exploit the tree of all possibilities using a depth-first method, i.e. , by back-tracking always preferring the action "stay". At each point in time we first add the operational profit of the current choice branch, subtract the switch-cost and all of the capital investment costs according to the choice in Step 6. For the rest of the period $\langle y_b, y_e \rangle$, we simply add maximum operational profit that the built modules can produce. If this estimation does not exceed the best period profit found so far, it is not worth stepping further forward — the branch is pruned and back-track occurs.

Moreover, under some circumstances a few choices can be eliminated (see Theorem 3).

9 Results

In this paper we analyzed different combinations of energy conversion and CO_2 capture and storage technologies in pulp and paper mills (see Section 5). The main interest was the choice of timing in switching from one CO_2 capture technology to the another triggered by the exogenous stochastic price process. These expected prices of the respective processes are consistent with the IIASA-MESSAGE model, which assesses the future of the global energy system up to 2100. Apart from gasification technology we also assessed recovery boiler (RB) technology, which can be considered to be state-of-the-art technology today. A direct comparison of recovery boiler technology with gasification technology is not presented in this paper due to the difficulties of developing consistent technological learning scenarios. We, therefore, present RB and gasification technologies (BLG) separately. We ran 200 simulations for each of the mentioned cases. We consider the total time period to be 50 years ($T = 50$), the retirement time of the equipment to be 25 years ($T_{\text{retire}} = 25$) and the discount rate to be 10%. Since our main interest was to find the expected optimal time to enter the carbon market, i.e., to start capturing CO_2, the presentation of the results will be biased towards CO_2 capture technology. The results will be presented in such a way that the sensitivity of optimal commitment to technological learning assumptions and various transportation distances for CO_2 can be assessed. We consider three different learning rates of 5%, 10%, 15% and three different transportation distances of 100 km, 400 km and 1000 km.

There is an option in the model to terminate the period prematurely, i.e. , earlier than after time T_{retire} expires. However, as expected and shown in Section 8, the results of simulations show that such a case almost never happens. Regardless of the type of module in all simulations the optimal time to start a new gasification period is always the year $T_{\text{retire}} + 1 = 26$.

The only situation when the period is perhaps terminated prematurely, is the last period. The last period is treated specially (see Section 6)—it is proportionally valued and this sometimes (but rarely) causes the premature termination of the second gasification period and starting of the third period a few years before the year T.

9.1 Case of the Recovery Boiler (MPM/RB and IPPM/RB)

When we run the market pulp mill with recovery boiler option (MPM/RB) we find that the capture option is almost never used. The build frequency is very low at around a frequency of 2 out of 200 simulations. In addition, the building of an MPM with RB and capture technology occurs in the last two years of the simulation only.

Not surprisingly, the CO_2 capture option is never chosen for the integrated pulp and paper mill with recovery boiler (IPPM/RB). This is the case even for a very ambitious learning rate of 15%. However, for recovery boilers, which is already a mature technology today, such learning rates might never materialize. This result can mainly be attributed to the steep increase in biomass requirement and to the high capital and operation costs of installing post-combustion capture technology.

9.2 Case of the Market Pulp Mill (MPM/BLG)

Black liquor gasification (BLG) on the other hand seems to be better adapted to a market situation where, in particular, carbon is priced. We find that for both the IPPM and the MPM, BLG_1 is consistently built in the first year. Nonetheless, the results differ with respect to the capture options. For MPMs the module BLG_3 is built in all cases, while built-time of BLG_2 vary over different choices of parameters. The building time of BLG_3 is concentrated within the first ten years of the second simulation period (i.e. , years 26–35). In cases of faster learning (15%) and short transportation distance (100 km) BLG_3 is committed to the market already in year 21 in 3 out of 200 cases. In general, the higher the learning rate, the sooner the first build of the CO_2 capture technology, which is because with the higher learning rate the technology becomes "sooner cheaper". (Note that lowering capital investment costs due to learning effect automatically lowers the operational costs as well, thus increasing the operational profit. However, as operational costs are paid on a yearly basis — unlike the capital investment costs that are paid on a 25 year long period-basis — the decrease of capital investment costs dominates). Figure 9 shows the frequency distribution of commitment for the three gasification technologies in the MPM environment for a small distance (100 km) and fast learning (15%). Under fast learning assumptions we observe that BLG_3 is added to BLG_1 prior to the end of the first gasification period. This effect is more pronounced in the case of small CO_2 transportation distances, where such replacement occurred in 159 out of 200 scenarios. However, the technological life time effect is still dominating given slow and medium learning rates. Only in 6 out of 200 simulations with slow and medium learning rates and given a small transportation distance it has been optimal to invest into BLG_3 technology prior to the year 26. For fast and more so for medium learning rates, at all distances, we observe a 'commitment spike' in the year 26, i.e. , in the first year of the second period (see Figure 10). The spike results from the fact that it is more profitable to postpone the building of the BLG module with CO_2 capture to the second period than to upgrade the existing BLG_1 by CO_2 capture technology just before the end of the first period. In most cases we observe a direct switch from BLG_1 to BLG_3. However, it was observed that in many cases BLG_2 acted as a transitory technology, that is, there was a switch from BLG_1 to BLG_2 a few periods before year 26. The appearance of the transitory technology in the MPM case was most pronounced in the fast learning case. For instance, with small transportation distances BLG_2 appeared in 47 out of 200 simulations for the case of fast learning and only in 12 out of 200 for the slow learning case (see Figure 11).

Our main interest has been to find the expected optimal commitment time for CO_2 capture technology. The results for the MPM/BLG_3 are depicted in Figure 12. We observe that under faster learning the transportation distance does not influence the commitment time significantly.

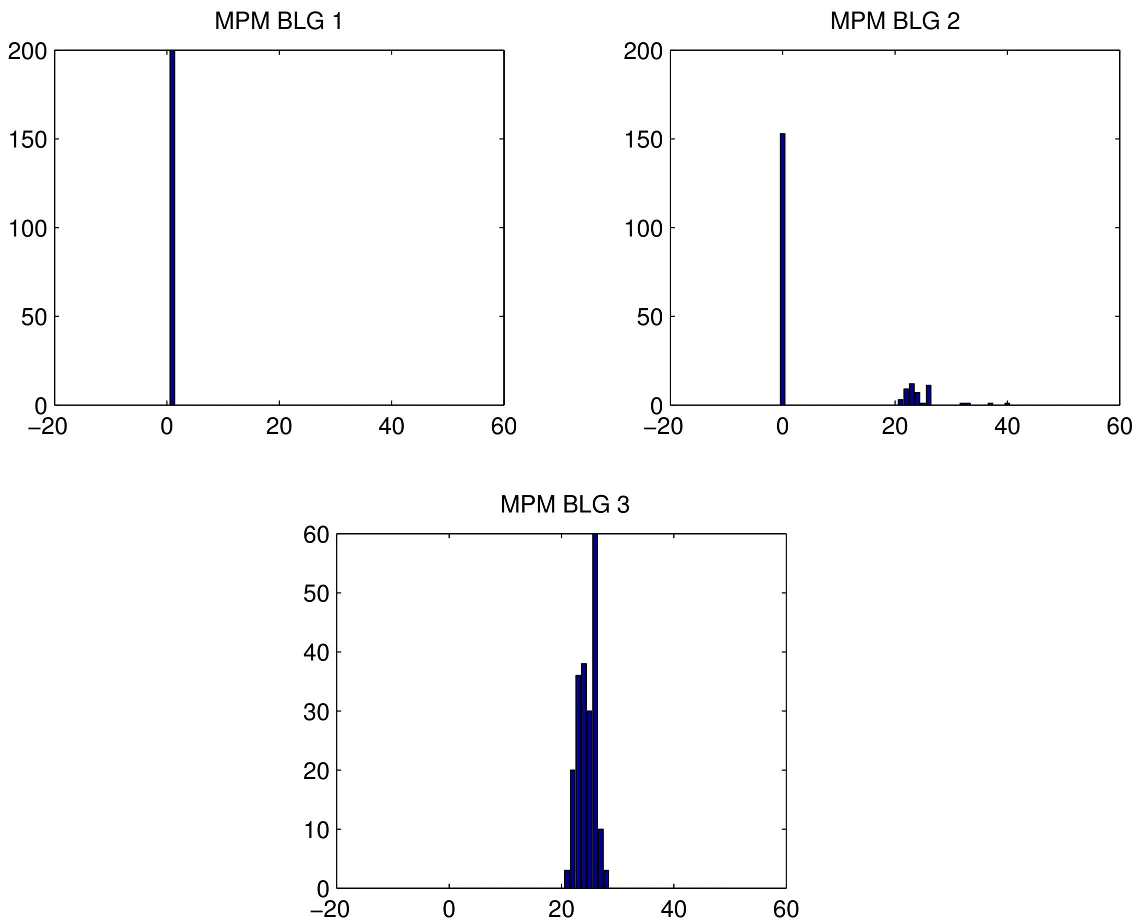


Figure 9: Frequency distribution of commitment time for MPM/BLG technologies: short distance (100 km), high learning rate (15%).

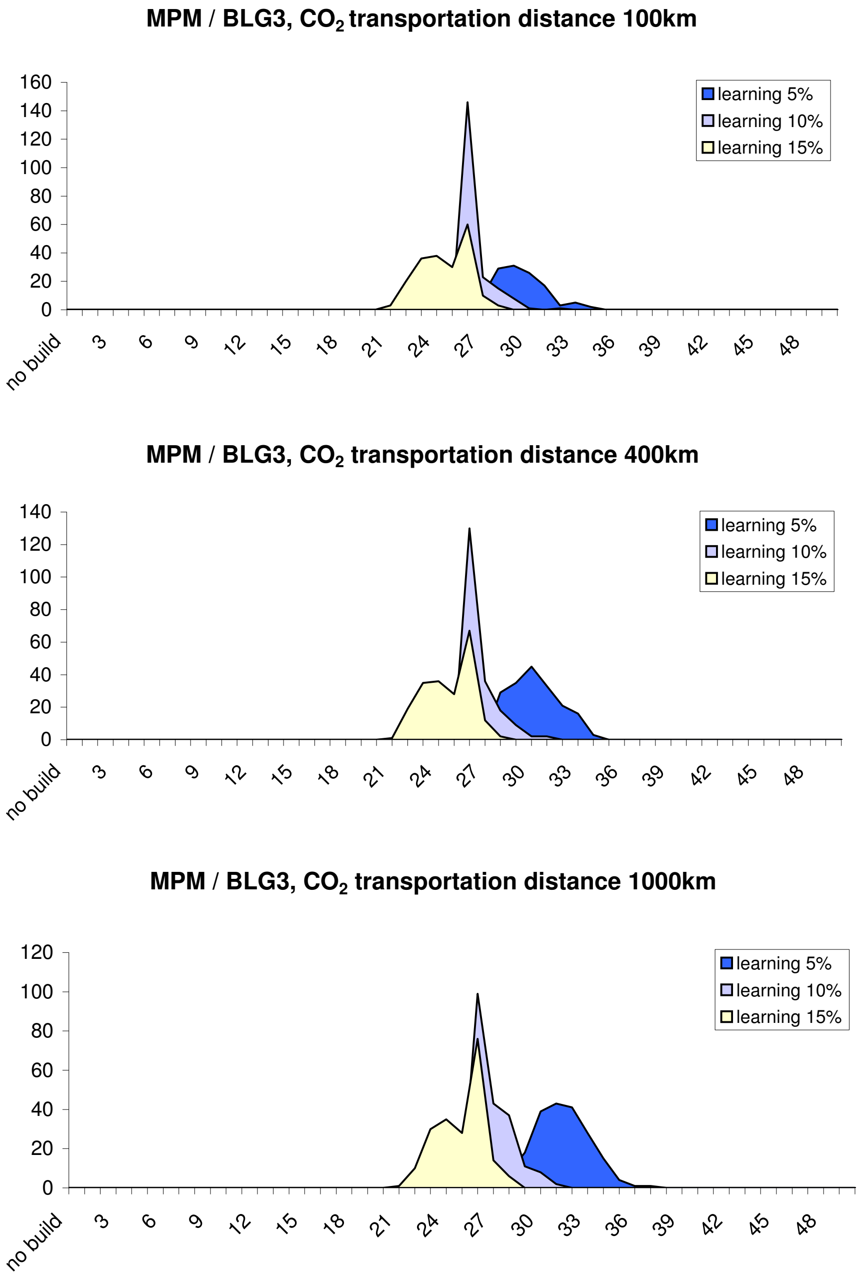
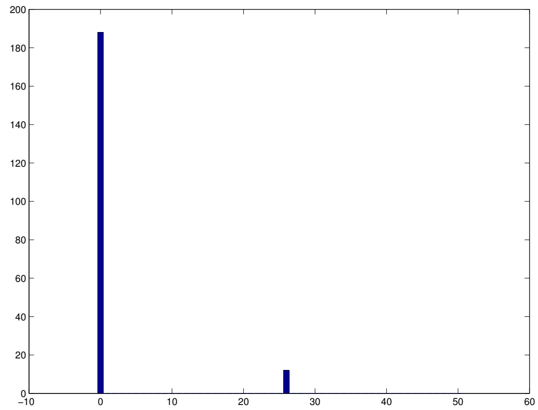
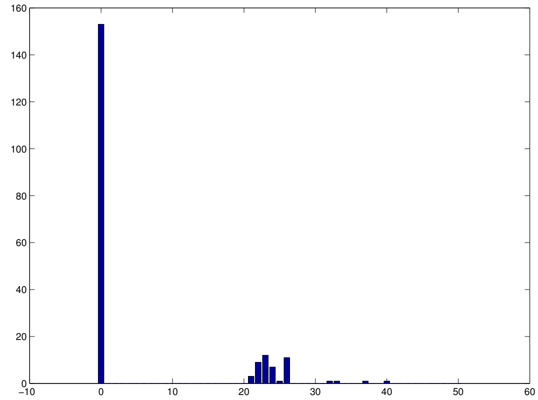


Figure 10: Frequency distribution of commitment time for MPM/BLG_3 technology.



(a) transportation distance 100km, learning rate 5%



(b) transportation distance 100km, learning rate 15%

Figure 11: Frequency distribution of commitment MPM/BLG$_2$ technology.

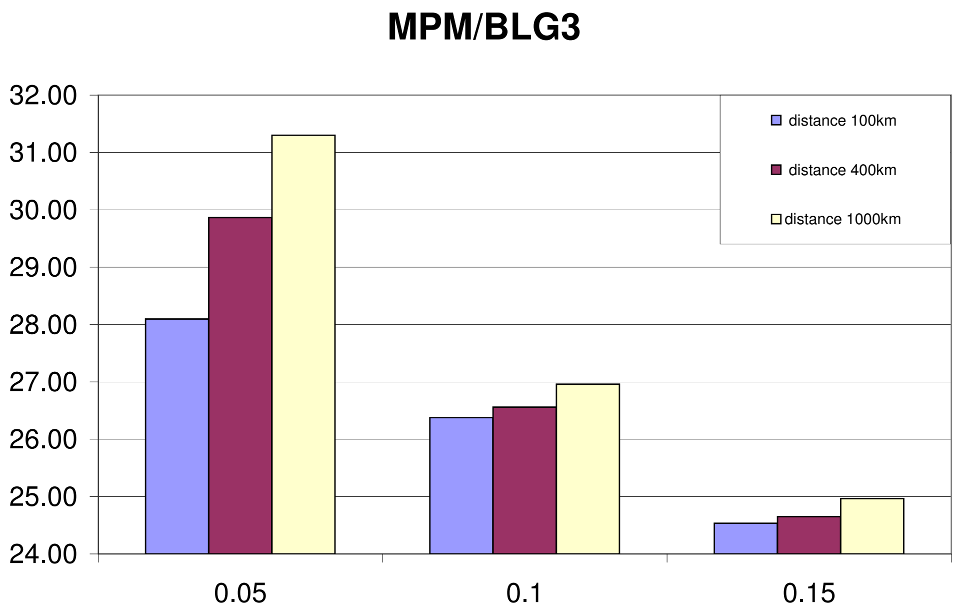


Figure 12: Learning effect on the expected commitment time for MPM/BLG technologies under different transportation distances.

9.3 Case of the Integrated Pulp and Paper Mill (IPPM/BLG)

Overall the scenarios with IPPM/BLG feature less variability. Similarly as in the MPM case, the module BLG_1 is always built in the first year of the first investment period. However, BLG_3 does not appear to be competitive and is only built in one percent of the scenarios. Figure 13 shows the distribution of commitment strategies for small transportation distances (100 km) and slow learning (5%). Independent of transportation distance

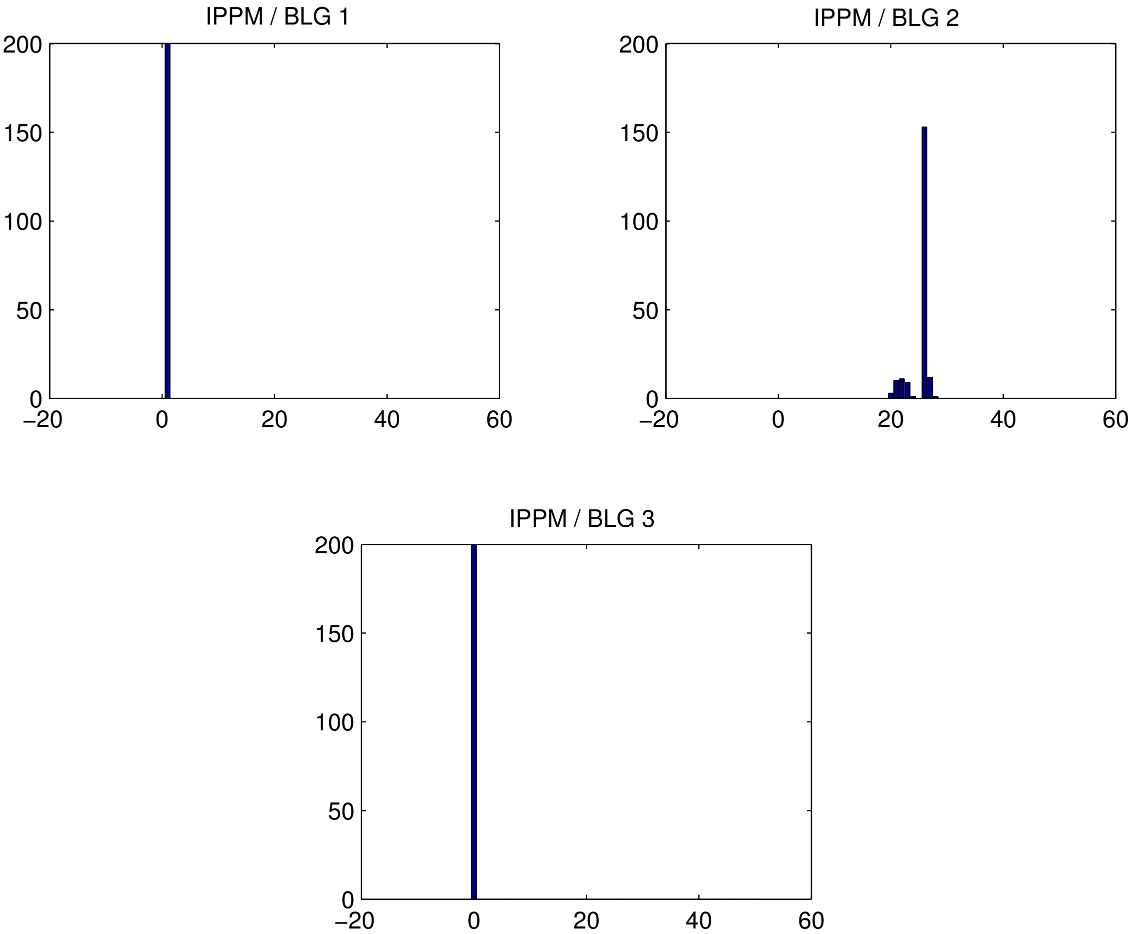


Figure 13: Frequency distribution of commitment time for IPPM/BLG technologies: short distance (100 km), low learning rate (5%).

for the slow learning assumption the timing to build BLG_2 is mostly dominated by the technical retirement restriction. For higher learning rates the technology switch occurs mostly prior to technical retirement and most interestingly prior to the MPM case.

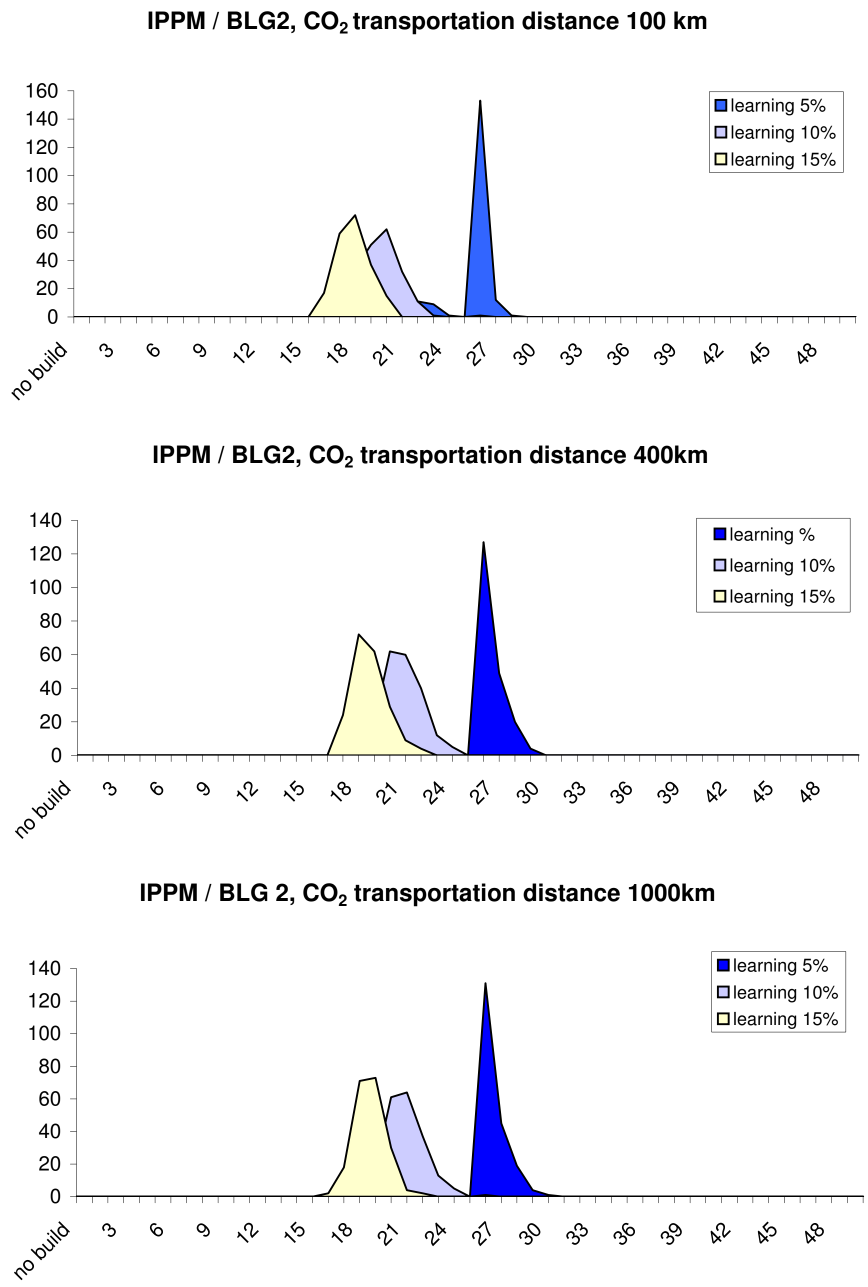


Figure 14: Frequency distribution of commitment time for IPPM/BLG_2 technologies.

Figure 14 shows that the expectation and the variance of the first commitment of BLG_2 are rather insensitive to transportation distance of CO_2—despite the rather high assumption on the transportation price for long distances of about 20USD per tonne of CO_2. Contrarily, the learning assumptions make a remarkable difference. In the case of high learning, irrespective of transportation distance, BLG_2 is committed by about 6 years earlier than in the case of low learning, which corresponds to a 22% reduction of the life time of the energy system of the IPPM.[11] In contrast to the MPM, the IPPM requires additional biomass to cover its energy demand. Therefore, the results are sensitive to the assumptions of additional biomass requirement.

Similarly as for MPM/BLG technology, we calculated the expected commitment time for CO_2 technology also for the case of IPPM/BLG. Figure 15 shows the expected optimal commitment time for the BLG_2 module. For almost all combinations of learning rates and transportation distances one expects the commitment of BLG_2 to occur already in the first period.

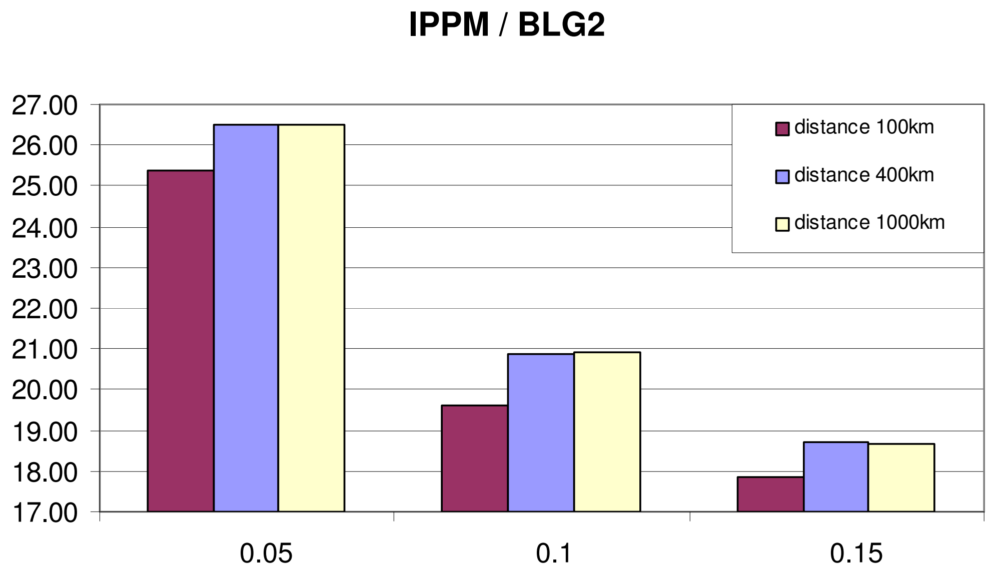


Figure 15: Learning effect on the expected commitment time for IPPM/BLG technologies under different transportation distances.

[11]Note that BLG_2 does not fully replace BLG_1. There are a number of parts that are used by both technologies.

10 Discussion

This paper is about the valuation of energy technologies which are expected to become competitive in the global energy market within the first half of this century. We developed a model that allows us to benchmark new and emerging energy technologies that are consistent with a variety of scenario families of global energy scenario models. Differences within the families are captured by the stochastic movement of input and output prices. In this study we have adapted the model in order to guarantee consistency with one of the leading IPCC global energy scenario models — the IIASA-MESSAGE model. Clearly, the results have to be interpreted within the set-up of the benchmark model, its implicit assumptions and the conditions underlying the scenario family that we have chosen. BLG technologies have not yet been included in such global energy scenario models, but have been mentioned as a low hanging fruit with respect to the implementation of CO_2 capture and storage technologies. Yet the optimal commitment strategy of this set of technologies has not yet been assessed in such scenarios. Our approach can also be considered novel as it considers investment decisions under uncertainty in an environment of multiple stochastic input-output relations. In our case inputs and outputs are stochastically correlated and there is a time-variant motion of the expected price.

There are a number of interesting general results that can be drawn from our model. First, it was observed that optimal timing has a spread of about 10 years, which is due to uncertainty in the input and output prices. In an environment with endogenous learning, i.e., learning as a function of the amount of accumulated capacity, such a commitment spread would considerably alter results in IPCC-type energy assessment models if they were to consider uncertainty. Second, in the face of uncertainty more flexible technologies (i.e., smaller sunk costs for technological upgrading like BLG_2) become competitive earlier and can act as transition technologies. However, such transition technologies procrastinate the implementation of technologies that turn out to be superior in the long-run (BLG_3). In a model of endogenous learning transition technologies could, thus, lead to slower overall technological change. In this sense the slowing effect of flexible transition technologies could be understood as a "technological risk premium" for the overall energy system, if the energy costs of the total system increases due to lost learning time for the superior technology. Third, the introduction of uncertainty is more likely to allow for a more technological diverse energy portfolio. In our simulations for the MPM/BLG case all three technological BLG options are present in the 10 year window around the end of the technological lifetime of BLG_1. Most interestingly, we observe that technological diversity increases with the rate of learning. This result can be explained by the fact that the leap-frogging gap, in our case to jump from BLG_1 directly to BLG_3, increases with high learning rates and must be bridged by a flexible transition technology. However, this insight is yet to be scrutinized in an environment of differential learning rates and the introduction of research and development investments driving learning rates.

Before, we start to consider the technological implications from the consistent, but uncertainty augmented analysis of BLG, we will shortly discuss differences with the insights gained from assessing BLG technologies so far. Observations from earlier economic assessments by Möllersten *et al.* (2004) and Möllersten *et al.* (forthcoming), which were based on the "CO_2 capture cost":

(i) Post-combustion CO_2 capture in IPPM with boiler technology slightly more economically attractive than pre-combustion capture in MPM with BLGCC.

(ii) The CO_2 capture cost in BLGCC systems without CO-shift was a less attractive alternative than capture in systems with CO-shift for both pulp mills and integrated pulp and paper mills. In those studies, however, the CO_2 capture costs were estimated considering static electricity and biomass prices (one fixed price for electricity and biomass, respectively). That approach gave only limited information about the economic feasibility of the studied technologies since it did not consider the impact of the expected upwards development and fluctuation of electricity and biomass prices along with the price of CO_2, which may be expected as CO_2 restrictions become more stringent. In this study the feasibility of CO_2 capture is sensitive to the price of biomass—or the cost incurred when large amounts of additional biomass is required. In this study post-combustion CO_2 capture is much less attractive because the applied method gives due credit to the superior efficiency of systems based on gasification (CO_2 capture leads to lower penalty in terms of decreased electrical efficiency and increased biomass requirement). Moreover, for BLGCC systems, the model chooses systems with CO-shift only for the MPM where no additional biomass is needed. In the case of IPPM the model prefers technology without CO-shift, capturing a smaller fraction of the carbon in the fuel, due to the dramatically increasing biomass requirement when a larger fraction of the carbon is captured. Thus, this model shows clear advantages of systems based on gasification.

There are a number of interesting insights from the modeling exercise with respect to technological features and its implications for competitiveness. The insensitive character of the results to transportation distance comes with some surprise since biomass-based energy conversion technologies are usually associated with a "logistical nightmare". We analyze systems with a fuel input between 300 to 500MW. Today, pulp mills manage to supply mills with biomass corresponding to around 700MW (half of the biomass ends up as fiber products), which proves that this is already logistically feasible. We also show that CO_2 transportation can be managed, assuming transportation costs up to 20USD/tCO_2. This is an important insight as larger scales seem to be economic, as we anticipated. Due to the low sensitivity to transportation costs the technology can be regarded as geographically flexible.

Overall, the results are sensitive to the additional biomass requirement except for the case of MPMs where, for BLG, no additional biomass is required. The timing and choice of technology seems to be more determined by the CO_2 price dynamics. For instance the IPPM BLG_3, which captures more CO_2 than BLG_2, appears in most cases more competitive, despite considerable higher capital investment costs.

The above suggests that the emphasis should be placed more upon developing efficient conversion systems (with minimized energy penalties) rather than on reducing cost for storage and transportation. Larger scales might be more competitive and this issue will need to be further investigated. In addition, despite the modular structure of the technologies there is still much room to increase overall flexibility of BLG technologies.

11 Conclusions

In this paper we have performed an uncertainty augmented benchmarking exercise of future energy technologies in a multiple input-output setting. Due to the high dimensionality of the problem we have specially designed a frugal algorithm to compute optimal commitment strategies using forward stochastic optimization. We apply our model to a portfolio of energy technologies in the pulp and paper industry. The technological benchmarking is consistent with scenario families of the IPCC global energy models. We consider the case of RB and BLG technology in MPM and IPPM in an investment under uncertainty. One stochastic input price signal for biomass and two stochastic output signals for electricity and carbon permits are considered. Such exercises could appear to be especially beneficial for strategy building of re-engineering existing engineered technologies in specialized research and development laboratories of the industry. Finally, the aim of this report was to obtain a first insight into this types of problems. In future research we are planning to continue with this analysis within the real options framework (Dixit and Pindyck, 1994). A major advantage of this approach is the ability to analyze better the value of flexibility and uncertainty. However, to implement the real options approach in such a complex model (three stochastic processes and seven different options) would require finding a very efficient way in order to be able to deal with the exponential computational time for a backward dynamic programming algorithm.

References

Berglin, N., Eriksson, T. and Berntsson, T. (1999). Performance Evaluation of Competing Designs for Efficient Cogeneration from Black Liquor. In: Proceedings of the Second Johan Gullichsen Colloquium, p. 55–67.

Brandberg, Ĺ., Ekbom, T., Hjerpe, C.-J., Hjortsberg, H., Landälv, I. and Sävbark, B. (2000). BioMeet: Planning of Biomass–Based Methanol Energy Combine — Trollhttan Region. Report No. XVII/4.1030/Z/98–368. Ecotraffic R&D AB and Nykomb Synergetics AB, Stockholm, Sweden.

Ceila, M.A. and Bachu, S. (2002). Geological Sequestration of CO_2: Is Leakage Unavoidable and Acceptable? In: Proceedings of the Sixth International Conference on Greenhouse Gas Control Technologies (GHGT–6), Kyoto, Japan.

Chiesa, P. and Consonni, S. (1999). Shift Reactors and Physical Absorption for Low-CO_2 Emission IGCCs. *Journal of Engineering for Gas Turbines and Power* 121(2):295–305.

David, J. and Herzog, H.J. (2000). The Cost of Carbon Capture. In: Williams, D.J., Durie, R.A., McMullan, P., Paulson, C.A.J. and Smith, A.Y. (eds.), *Proceedings of the Fifth International Conference on Greenhouse Gas Control Technologies (GHGT-5).* CSIRO Publishing, Collingwood, Australia, p. 985–990.

DOE (1999). Carbon Sequestration Research and Development. Office of Science, Office of Fossil Energy, U.S. Department of Energy, Washington DC.

Dixit, A. and Pindyck, R.S. (1994). *Investment under Uncertainty.* Princeton University Press, Princeton, NJ.

Ekström, C., Blumer, M., Cavani, A., Hedberg, M., Hinderson, A., Svensson, C.-G., Westermark, M., Erlström, M. and Hagenfeldt, S. (1997). Technologies and Costs in Sweden for Capture and Storage of CO_2 from Combustion of Fossil Fuels for Production of Power, Heat, and/or Transportation Fuels. Vattenfall Utveckling AB, Stockholm, Sweden (in Swedish).

FAO (2003). Statistical Databases. Available on the Internet: i http://www.fao.org.

Falkowski, P., Scholes, R.J., Boyle, E., Canadell, J., Canfield, D., Elser, J., Gruber, N., Hibbard, K., Högberg, P., Linder, S., Mackenzie, F.T., Moore, B., Pedersen, T., Rosenthal, Y., Seitzinger, S., Smetacek, V. and Steffen, W. (2000). The Global Carbon Cycle: A Test of Our Knowledge of Earth as a System. *Science* 290(5490): 291–296.

Farla, J., Blok, K., and Schipper, L. (1997). Energy Efficiency Developments in the Pulp and Paper Industry. *Energy Policy* 25(7–9), p. 745–758.

Freund, P. and Davison, J. (2002). General Overview of Costs. In: Proceedings of the IPPC Workshop on Carbon Dioxide Capture and Storage, Regina, Canada.

Göttlicher, G. and Pruschek, R. (1997). Comparison of CO_2 Removal Systems for Fossil-Fuelled Power Plant Processes. *Energy Conversion and Management* 38(Suppl), S173–S178.

Grimston, M.C., Karakoussis, V., Fouquet, R., van der Vorst, P., Pearson, M., Leach, M., (2001). The European and Global Potential of Carbon Dioxide Sequestration in Tackling Climate Change. *Climate Policy* 1, 155–177.

Holloway, S. (2002). Storage of Fossil Fuel-derived Carbon Dioxide Beneath the Surface of the Earth. *Annual Rev. Energ. Env.* 26: p. 145–166.

IEA (2002). Transmission of CO_2 and Energy. Report No. PH4/6. IEA Greenhouse Gas R&D Programme, Stoke Orchard, United Kingdom.

IPCC (2001a). *Climate Change 2001: The Scientific Basis.* Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge.

IPCC (2001b). *Climate Change 2001: Mitigation.* Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge.

Kaarstad, O. (200). CO_2 and Energy—The Sleipner CO_2 Project and Possible Future Roles of Underground Storage. (CD-ROM), Statoil, Trondheim.

Khrushch, M., Worrell, E., Price, L., Martin, N. and Einstein, D. (1999). Carbon Emissions Reduction Potential in the Chemicals and Pulp and Paper Industries by Applying CHP Technologies. Report No. LBNL-43739, Lawrence Berkeley National Laboratory, Berkeley, CA.

Lackner, K.S. (2003). A Guide to CO_2 Sequestration. *Science* 300(5626):1677–1678.

Larson, E.D., Kreutz, T. and Consonni, S. (1999). Combined Biomass and Black Liquor Gasifier/Gas Turbine Cogeneration at Pulp and Paper Mills. *Journal of Engineering for Gas Turbines and Power* 121(3):394–400.

Larson, E., Consonni, S. and Kreutz, T. (2000). Preliminary Economics of Black Liquor Gasifier/Gas Turbine Cogeneration at Pulp and Paper Mills. *Journal of Engineering for Gas Turbines and Power* 122(3):255–261.

Lindeberg, E. (1999). Future Large-scale Use of Fossil Energy will Require CO_2 Sequestering and Disposal. In: Proceedings of the Minisymposium on Carbon Dioxide Capture and Storage, Gothenburg, Sweden.

Mannisto, H. and Mannisto, E. (1999). The Impact of the Kyoto Agreement on Forest Industry in Canada. In: Preprints of the 85th Annual Meeting of the Pulp and Paper Technical Association of Canada, Montreal. Pulp and Paper Technical Association of Canada, Montreal, p. B417–B22.

Martin, N., Anglani, N., Einstein, D., Khrushch, M., Worrell, E. and Price, L.K. (2000). Opportunities to Improve Energy Efficiency and Reduce Greenhouse Gas Emissions in the US Pulp and Paper Industry. Report No. LBNL–46141. Lawrence Berkeley National Laboratory, Berkeley, CA.

Maunsbach, K. (1999). Opportunities for Efficient Use of Biomass in the Pulp and Paper Industry. Licenciate treatise No. TRITA-KET R108. Department of Chemical Engineering and Technology, Royal Institute of Technology, Stockholm, Sweden.

Maunsbach, K., Isaksson, A., Yan, J., Svedberg, G. and Eidensten, L.J. (2001). Integration of Advanced Gas Turbines in Pulp and Paper Mills for Increased Power Generation. *Journal of Engineering for Gas Turbines and Power* 123(4): 734–740.

Messner, S. and Schrattenholzer, L. (2000). MESSAGE-MACRO: Linking an Energy Supply Model with a Macroeconomic Module and Solving it Iteratively. *Energy* 25:267–282.

Möllersten, K. (2002). Opportunities for CO_2 Reductions and CO_2-lean Energy Systems in Pulp and Paper Mills. Doctoral thesis No. TRITA-KET R161. Department of Chemical Engineering and Technology, Royal Institute of Technology, Stockholm, Sweden.

Möllersten, K., Yan, J. and Moreira, J.R. (2003a). Potential Market Niches for Biomass Energy with CO_2 Capture and Storage — Opportunities for Energy Supply with Negative CO_2 Emissions. *Biomass and Bioenergy* 25(3): 273–285.

Möllersten, K., Yan, J. and Westermark, M. (2003b). Potential and Cost-effectiveness of CO_2 Reductions through Energy Measures in Swedish Pulp and Paper Mills. *Energy* 28(7): 691–710.

Möllersten, K., Gao, L., Yan, J. and Obersteiner, M. (2004). Efficient Energy Systems with CO_2 Capture and Storage from Renewable Biomass in Pulp and Paper Mills. *Renewable Energy* 29(9):1583–1598.

Möllersten, K., Gao, L. and Yan, J. (forthcoming). CO_2 Balances and Mitigation Costs of Advanced CHP Systems with CO_2 Capture in Pulp and Paper Mills. Submitted to *Mitigation and Adaptation Strategies for Global Change*.

Nakicenovic, N. and Riahi, K. (2003). An Assessment of Technological Change across Selected Energy Scenarios. Research Report RR-02-005 (Reprint from a WEC report). International Institute for Applied Systems Analysis, Laxenburg, Austria.

Obersteiner, M., Azar, C., Kauppi, P., Möllersten, K., Moreira, R., Nilsson, S., Read, P., Riahi, K., Schlamadinger, B., Yan, J. and Ypersele, J.P. (2001). Managing Climate Risk. *Science* 294(5543):786–787.

Parson, E.A. and Keith, D.W. (1998). Fossil Fuels Without CO_2 Emissions. *Science* 282(5391):1053–1054.

Riahi, K., Rubin, E.S, Taylor, M. R., Schrattenholzer, L. and Hounshell, D. (2004). Technological Learning for Carbon Capture and Sequestration Technologies. *Energy Economics* 26(2004):539–564.

Riahi, K. and Roehrl, R.A. (2000). Greenhouse Gas Emissions in a Dynamics-as-usual Scenario of Economic and Energy Development. *Technological Forecasting and Social Change*, Vol. 63(3).

RCEP (2000). Energy — The Changing Climate. Royal Commission on Environmental Pollution (RCEP), London, 22nd Report.

Siro, M. (1984). First Finnish Kraft Pulp and Paper Mill Iindependent of Oil as an Energy Source. In: Proceedings of the 1984 TAPPI Pulping Conference, p. 591–595.

STFI (2000). The Ecocyclic Pulp Mill, Phase 1. Final report KAM1 1996–1999. Swedish Pulp and Paper Research Institute (STFI), Stockholm.

Warnqvist, B. (2000). Techno-economic Evaluation of Black Liquor Gasification Processes. Report No. 698, Varmeforsk, Stockholm, Sweden (in Swedish).

Wigley, T.R., Richels, R. and Edmonds, J. (1996). Economic and Environmental Choices in the Stabilization of Atmospheric CO_2 Concentrations. *Nature* 359(6562), 240–243.

Williams, D.J., Durie, R.A., McMullan, P., Paulson, C.A.J. and Smith, A.Y. (eds.) (2000). *Proceedings of the Fifth International Conference on Greenhouse Gas Control Technologies* (GHGT–5). CSIRO Publishing, Collingwood, Australia.