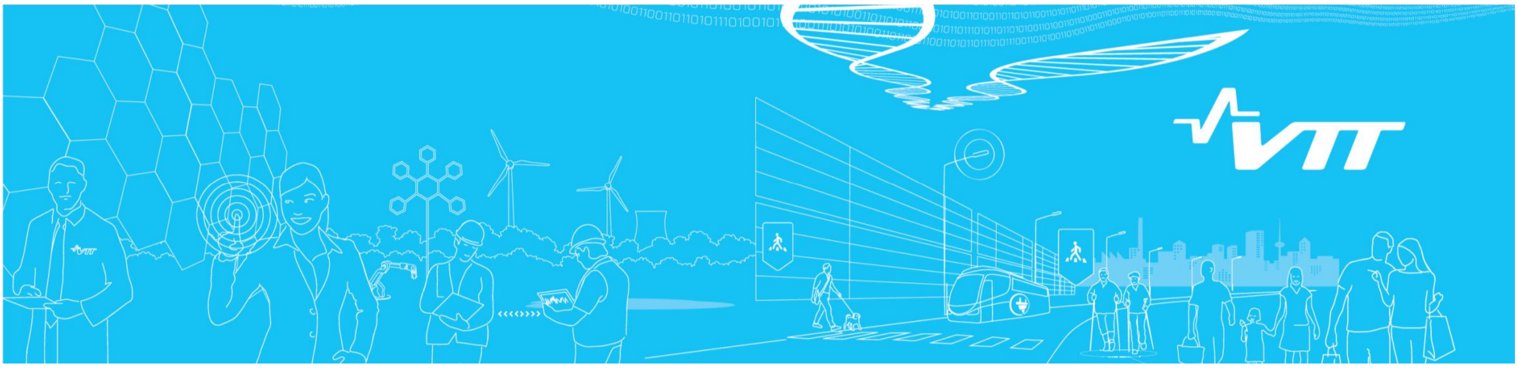

RESEARCH REPORT

VTT-R-05739-14

BEST: Case India project

Case studies on the economic feasibility of biomass use in condensing power and CHP plants in India

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Summary

Two case studies for evaluating the feasibility of biomass use in energy production in India were carried out. The first study considered investment in to a new dedicated biomass power plant. Two alternative technologies were compared. The first option was "Indian technology" characterised by low electrical efficiency, low level of automation but also low investment and operation costs. The other option was to have a more "Western approach" with higher efficiency and automation level with the drawback of higher costs.

In the second study the feasibility of a multifuel CHP plant capable of condensing mode operation was considered. Operation on different fuel mixtures, consisting of Indonesian coal, biomass briquettes and domestic coal, was studied as well as operation on CHP and condensing modes.

In the studies, biomass raw materials were first selected based on their availability and actual use in the selected state, Tamil Nadu. Then the fuel supply chains were specified and the costs of each phase were calculated leading to a biomass price at the power plant gate for each biomass type.

At the end-user site, the studies considered e.g. combustion technology, boiler specifications, plant operation, investment and O&M costs, electricity prices and subsidies. Using the biomass prices and all the other relevant data, the overall economic feasibility was then evaluated. Rather than presenting results only at some fixed parameters, interactive toolkits, which allow the user to study the effects of selected variable, were developed.

In the dedicated biomass cases, only the Western technology plant was found to be feasible: the higher efficiency more than compensated the higher costs in this case. Without subsidies the Western technology plant would have been clearly unfeasible too.

In the case of multifuel CHP plant, CHP production was found to be favourable compared to condensing power production although this was found to be highly dependent on the price obtained for the process steam. Of the studied fuel mixtures, co-firing of cheap domestic coal with imported coal was found to be the most economical option. Using biomass in co-firing was not attractive as there are no subsidies available and because briquetting further increased the already high price of biomass. If the plant would have been qualified to obtain Renewable Energy Certificates for the biomass based electricity portion, co-firing biomass would have been equally profitable as using 100% imported coal.

Confidentiality	Confidential

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Preface

The project Case India is a part of the Sustainable Bioenergy solutions for tomorrow (BEST) programme, which is joint research program by FIBIC Ltd, and CLEEN Ltd. BEST programme is funded by the Finnish Funding Agency for Technology and Innovation, Tekes.

The Case India project was scheduled for 2013–2014 and it is divided into four tasks: (1) biomass resources, (2) biomass supply technology, (3) biomass utilisation for energy and (4) biomass consumption challenges.

This report deals with economic feasibility evaluations for biomass based power and combined heat and power generation by means of case studies and thus addresses mostly task 3.

Work has been conducted in-operation with Valmet, Fortum and UEF.

Jyväskylä 10.03.2015

Authors

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1. Introduction

In 2012, the total installed direct biomass electricity capacity in India was 1 200 MWe, which is only about 0.6 % of the total capacity. The estimated biomass power potential is about 18 000 MWe. Currently biomass is mainly used in dedicated condensing power plants, whose average capacity is only some 10 MWe. The plants can use up to 20–30 different kinds of agricultural and woody residues in order to guarantee continuous biomass supply throughout the year. Examples of the biomass fuels are coconut fronds, cotton stalk, plywood residues and *prosopis juliflora*.

Main challenge for biomass power plants seems to be the undeveloped fuel supply chains. Biomass prices have also been found to rise quickly after the power plant has been commissioned and the subsidies have been insufficient.

The goal of this work was to evaluate the economic feasibility for investing into:

1) a condensing dedicated biomass power plant (Case I)

2) a combined heat and power (CHP) plant suitable for co-firing biomass with coal (Case II)

The first case represents the typical Indian biomass power plant and the second case is an alternative way – which would solve the availability and unreasonable price increase issues – for utilising biomass in large scale. Plants were fictional and they were thought to be located in the Tamil Nadu state.

In the studies, biomass raw materials were first selected based on their availability and actual use in the selected state, Tamil Nadu. Then the fuel supply chains were specified and the costs of each phase were calculated leading to a biomass price at the power plant gate for each biomass type. Biomass gate prices were then used as one key parameter, when the total operation and economic models for power plants were developed.

2. Approach

When evaluating the feasibility of a power plant investment, various aspects must be considered. These include for example:

- Investment cost
- Operation and maintenance (O&M) costs
- Fuel costs
- Prices of the produced electricity and steam/heat
- Ash disposal costs (or profit for ash utilisation)

These in turn are dependent on e.g.:

- Boiler specifications, such as the boiler and electrical efficiencies, heat-to-power ratios and peak load utilisation hours (or capacity factors)
- Available fuels and their supply chains
- Policies/subsidies/legislation

For obtaining reasonable India specific values, several visits to Indian biomass power plants have been carried out by the project group. Data has also been collected from the public domain and some values are estimated based on VTT's expertise on this field.

However, as values for some variables (such as investment or O&M costs) are difficult to obtain and some (such as electricity price, subsidies) can change quickly, the aim was to build interactive tools that would allow the user to change the inputs and then see in illustrative way, how the changes affect the results. The case specific toolkits are shortly described in this report.

3. Biomass fuels in the case studies

3.1 Biomass potential in Tamil Nadu

The total biomass power potential in Tamil Nadu in 2002–2004 was 1590 MWe of which 1 160 MWe was agro biomass. (Table 1) There are many different kinds of agro biomasses available for energy use and the main ones are paddy straw and paddy husk, maize stalk and husk, groundnut stalk and shell and cotton stalk.

The total wasteland area in Tamil Nadu is 7 549 km^2. The potential of biomass residues from wasteland is 106 MWe representing about 0.77 million tons of stalks, branches, leaves, twigs and bark from different logging operations of bushes and trees. There is a lot of additional biomass power potential in cultivating energy crops as a fuel on wasteland. The forest biomass power potential is 324 MWe. The forest biomass sources are mainly the same as from wasteland (Leinonen et al. 2014).

The total installed electricity production capacity in Tamil Nadu was 7 405 MWe in 2011 (TEDA 2014b). The total installed biomass power and cogeneration in sugar mills capacity was 659 MWe in 2014. From this the biomass electricity capacity was 226 MWe (TEDA 2014a).

The biomass power plants utilise agroindustry residues as the main biomass type. The consumption of biomass for energy in Tamil Nadu is about 1.7 million tons assuming that the energy content of biomass as received is 3.95 MWh/ton and that the electrical efficiency is 20 %. Most of the plants are located in the south of Tamil Nadu where adequate biomass from agriculture and wasteland is available.

Table 1. Biomass power potential in Tamil Nadu state (Leinonen et al. 2014)

Biomass type	Potential, MWe
Agro biomass	1160
Biomass from wasteland	106
Forest biomass	324
All together	1590

3.2 Selection of the biomass fuels for the case studies

In India power plants have to use different kinds of biomass fuels because the agro biomass residues are generating periodically depending on the growing season. (Table 2) Using several fuels the power plant can ensure continuous biomass supply throughout the year (Leinonen et al. 2014). A period of 25–30 days is available after harvesting of kharif and rabi crops for sowing/planting the next crop. This period is enough to collect and store the agro residues in a cost effective and proper way for biomass delivery later for energy use (Dubey et al. 2010).

The fictional case plants considered in the studies were thought be located in Tamil Nadu state. Based on the availability and the actual use in Tamil Nadu, the biomass fuels selected to be prosopis juliflora, coconut fronds and cotton stalks. For these fuels comprehensive fuel analyses were also carried out by Valmet Power in the project. In addition, plywood residues were considered as a possible biomass fuel but the supply chain was not analysed in detail and no chemical analyses were conducted.

Table 2. Seasonal availability of agricultural crop residues in India (Leinonen et al. 2010)

Residue/month	January	February	March	April	May	June	July	August	September	October	November	December
Maize stalk												
Maize cobs												
Cotton stalks												
Mustard husk												
Jute mesta sticks												
Rice husk												
Groundnut shells												
Arhar stalks												

3.3 Biomass fuel descriptions

Coconut fronds are the stiff mid-ribs (stem) of the coconut leaves (Figure 1). Roughly 173 coconut trees are planted on one hectare of land. Each tree gives approximately 12 coconut fronds per year (1 frond per month) each weighing 6–8 kg (wet basis). The annual yield of coconut frond is 14–18 wet tons per ha per year.

Figure 1. Coconut trees (left) and coconut frond in the heap (right). (Leinonen et al. 2014)

Prosopis juliflora is a fast growing tree and it is well-adapted to warm and dry tropical climates (Figure 2). It grows vigorously in dry lands of Southern Tamil Nadu and it is available for supply throughout the year. A lot of research for cultivation of prosopis juliflora for energy purposes has been carried out. The cultivation of prosopis for energy purposes is just starting Tamil Nadu. At the moment only stems are used for energy. The branches are used as cattle fodder. (Leinonen et al. 2014)

Figure 2. Prosopis juliflora. (Leinonen et al. 2014)

Cotton is a perennial crop but is it is primarily grown as an annual crop in order to prevent the growth of pest population (Figure 3). Cotton is a soft, fluffy staple fibre that grows in a boll around the seeds of cotton plants. Cotton is still a main raw material for the world's textile industry. Most of the cotton stalk generated in India (23 mill tons/a) is treated as waste though a small part of it is used as domestic fuel. (Cotton India 2014) At the moment majority of cotton stalks is burnt on the fields after the harvest of cotton crop (Figure 3). (Leinonen et al. 2014)

Figure 3. Cotton field (left) and burning cotton stalk on the field (right). (Leinonen et al. 2014)

Plywood residues come from the mechanical forest industry sites and they include both clean wood and plywood. They are also available throughout the year.

Figure 4. Plywood residues. (Leinonen et al. 2014)

3.4 Biomass fuel properties

Table 3 shows the analysis results for the selected biomass fuels. The most notable conclusions are:

- high chlorine contents especially in coconut fronds (2.8 wt-%) indicating clear high temperature corrosion risks for superheaters at elevated steam parameters
- high alkali (Na+K) content in coconut fronds and cotton stalks indicating bed agglomeration (in fluidised bed boilers) and fouling risks for heat transfer surfaces
- even the woody prosopis juliflora contains quite amounts of chlorine and alkali

It should however be pointed out that these represent only single samples and it is possible that these are close to worst case scenario specially in the case of coconut fronds.

Table 3. Biomass fuel properties (provided by Valmet Power)

Analysis	Unit	Coconut frond	Cotton stalk	Prosopis juliflora
Volatiles	wt.-% d.s.	70.00	75.00	80.00
Fixed carbon	wt.-% d.s.	23.00	22.00	19.00
Ash 815 °C	wt.-% d.s.	7.40	3.20	1.40
HHV dry	MJ/kg	16.57	18.65	19.31
LHV dry	MJ/kg	15.45	17.42	18.04
C	wt.-% d.s.	43.9	47.4	48.9
H	wt.-% d.s.	5.1	5.6	5.8
N	wt.-% d.s.	0.19	0.56	0.35
Cl	wt.-% d.s.	**2.800**	**0.790**	**0.210**
S	wt.-% d.s.	0.110	0.140	0.030
O	wt.-% d.s.	40.5	42.3	43.3
Major ash forming elements in fuel				
Al	mg/kg d.s.	120	75	34
Si	mg/kg d.s.	2200	238	84
Ti	mg/kg d.s.	52	4	3
Na	mg/kg d.s.	**12200**	**3200**	175
Mg	mg/kg d.s.	12496	1225	238
K	mg/kg d.s.	**2700**	**5855**	**3150**
Ca	mg/kg d.s.	15300	4357	3430
Fe	mg/kg d.s.	72	45	12
P	mg/kg d.s.	1900	613	203
Mn	mg/kg d.s.	9	6	5

4. Case study I – Dedicated biomass power plant

4.1 Overall description

The economic feasibility for investing into a new dedicated biomass power plant having fuel power of 50 MW was studied with two fictional plants having different designs. The first plant was based on "Indian technology" characterised by low electrical efficiency, low level of automation but also low investment and operation costs. The other plant was thought to have a more "Western approach" with higher efficiency and automation level with the expense of higher investment and O&M costs. The plants were thought to be located in Tamil Nadu and fuels were thought to be agro and woody residues.

4.2 Electricity sales and subsidies

It is assumed that produced electricity is sold to both private industry companies and to governmental grid. Prices obtained from private companies are clearly higher but the difference is partly negated by wheeling charges that have to be paid for using the grid infrastructure. It was assumed that 80 % of the electricity is sold to private industries.

In India, plants may earn Renewable Electricity Certificates (REC) from biomass based electricity production (floor price 1.5 Rs/kWh = 17.8 €/MWh, one € equals 84.5 Rs) if they are not using other subsidies such as feed-in tariff (also known as preferential tariff). When the plant has opted for the REC mechanism, the electricity sold to the state's distribution licensee must be sold at a price not exceeding the average pooled purchase cost.

In this case study it is assumed that the plant is registered under REC mechanism and that the price obtained for electricity sold to the distribution licensee is 40 €/MWh and 80 €/MWh for private companies. Wheeling and distribution charges are 20 €/MWh.

4.3 Power plant descriptions

4.3.1 Fuels

Both power plants were thought to be operated with the following annual fuel mix:

- Prosopis juliflora – 70 % (as received, energy basis)
- Coconut fronds – 10 %
- Plywood residues – 20 %

Prosopis juliflora was considered as the main fuel. Due to extremely challenging combustion properties of the coconut fronds (Table 2) their share was limited to 10 % on annual basis. Plywood residues can also contain elevated amounts of alkalis and it was assumed that their availability is also limited.

Plywood residues and prosopis juliflora are available throughout the year and coconut fronds can be harvested outside the monsoon season, from November to May.

Fuel supply chains are described later in chapter 4.4.

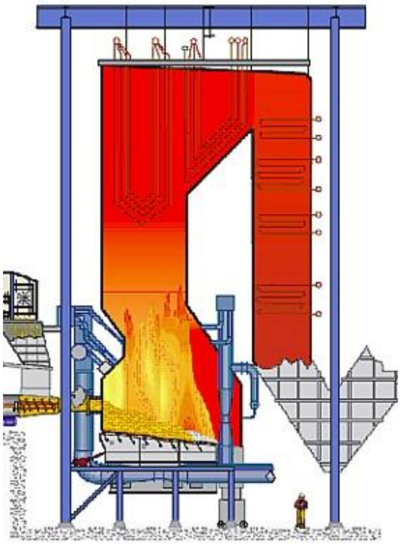
4.3.2 Indian technology plant

The 'Indian technology plant' is based on moving grate firing technology and has live steam parameters of 440 °C, 60 bar. (Figure 5) The plant has an air-cooled steam condenser and its in-house electricity consumption is 10 % of the total production leading to a net electrical efficiency (fuel-to-power) of 21 %.

The plant is operated in three shifts (24x7). Due low automation and instrumentation level, the total staff number is high, 100 (permanent 40, temporary 60).

Based on the plant visits carried out during the project, the following operational issues were assumed to take place and thus affect the O&M costs and peak load operation hours:

- Superheaters need to be replaced every fourth year due to corrosion (despite the low steam parameters)
- Ash clogging happens every now and then due to unburnt biomass residues in the boiler and ash removal systems, unburnt carbon in ash 12 %
- Boiler maintenance break is one month per year
- Additionally once in a month there is a 2 day off-period, when the boiler is shut down for cleaning of the deposits in the superheater area.
- On-line sootblowing of the superheaters takes place twice per every shift



Moving grate fired boiler

Capacity: 50 MW_{fuel}

Live steam: 440 °C, 60 bar

Fuels: 100% biomass

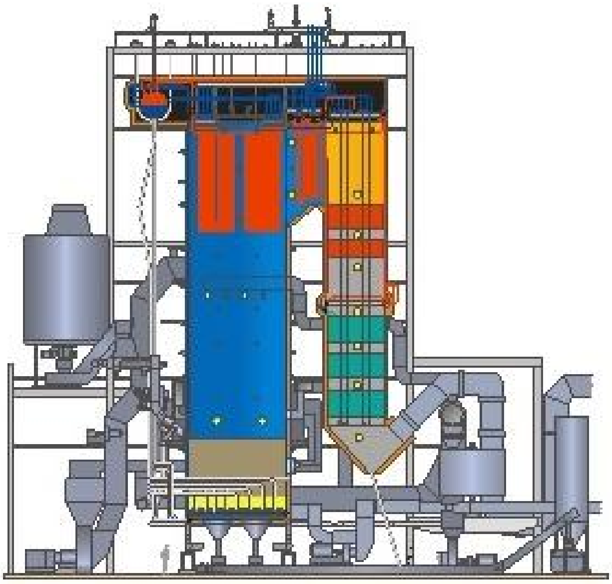
Figure 5. Grate fired boiler. (Picture is courtesy of B&W Volund, specifications have been made by the authors and they do not represent any actual plant)

4.3.3 Western technology plant

The ‘Western technology plant’ has a bubbling fluidised bed (BFB) boiler with live steam parameters 505 °C, 90 bar. (Figure 6) Net electrical efficiency (fuel-to-power) is 30 %. The plant is operated in three shifts (24x7) and the total staff number is 50 (permanent 20, temporary 30).

Boiler operation related assumptions:

- Chemical additives for combustion are used in order to prevent bed agglomeration and excessive corrosion and fouling (this increases variable O&M costs markedly but allows more reliable boiler operation)
- Superheaters need to be replaced only every twelfth year due to corrosion
- Ash clogging is not an issue, unburnt carbon in ash 3 %
- Boiler maintenance break is one month per year
- Additionally once in a year there is a 2 day off-period, when the boiler is shut down for cleaning of the deposits in the superheater area
- On-line sootblowing of the superheaters takes place twice per every shift with efficient sootblowers



Bubbling fluidized bed (BFB) boiler

Capacity: 50 MW_{fuel}

Live steam: 505 °C, 90 bar

Fuels: 100% biomass

Figure 6. Schematic of bubbling fluidised boiler. (Picture of courtesy of Valmet Power, specifications have been made by the authors and they do not represent any actual plant)

4.3.4 Common assumptions

The following common assumptions are made for both plants:

- Plants aim to operate full load all the time between planned (and un-planned) maintenance breaks.
- Dust emissions are controlled with ESP. Other plant emissions are not strictly regulated.
- The ash residuals are supplied to the farmers at free of cost and they are used as fertilizers in the agricultural land.

4.3.5 Summary of the main assumptions

A summary of the most relevant parameters is given in Table 4. Rough breakdown of capital costs for both plants are shown in Table 5.

Table 4. Summary of default parameters

Parameter	Indian	Western
Combustion technology	Moving grate	BFB
Fuel power, MW	50	50
Electrical efficiency, net, %	21	30
Net electricity output, MW	10.5	15
Peak load utilisation, h/a	4520*	5000
Number of persons (full time / part time)	40/60	20/30
Variable O&M, €/MWh_{fuel}	1.5	2.5
Fixed O&M, €/kW_{fuel}	8	10
Total investment costs, M€	12.5	20
Parameter	**Common**	
Personnel costs €/a/person	1800	
Electricity price, €/MWh (industry/governmental grid)	80/40	
Wheeling charges, €/MWh	20	
Biomass REC, €/MWh	17.8	
Discount rate, (real terms)	8 %	
Technical lifetime, a	25	

*lower peak utilisation hours are due to monthly shutdowns for boiler cleaning

Table 5. Capital cost breakdown

Cost component	Indian	Western
1.Machinery&Equipment *-Boiler, turbine, fuel handling, auxiliaries, automation and electrification*	9	14.4
2. Construction work *-Buildings, sitework, foundation, connections*	1.5	2.4
3. Design & Supervision (10 % of 1. and 2.)	1.1	1.7
4. Contingencies (5 % of 1-3.)	0.6	0.9
5. Interest during construction (3 % of 1-4.)	0.4	0.6
TOTAL, M€	**12.5**	**20.0**

4.4 Biomass fuel supply chains

4.4.1 General information of the harvesting and supply chain in India

In the case study, it is assumed that the biomass harvesting and supply is carried out using the technologies and practices that are currently utilised in India. Generally the biomass is procured at the farm by the farmer. The procured biomass is delivered and sold to the power plant by the biomass supplier (trader). Sometimes farmers sell and transport the biomass directly to the power plant with their own vehicle (Figure 7). The power plant pays the registered suppliers in 30 days from the delivery date (Leinonen et al. 2014).

The biomass price at the power plant was 14.2–41.4 €/ton (1 200–3500 Rs/ton) in 2014. Of the main fuels, the cheapest one was coconut residues and groundnut shells was the most expensive type (Leinonen et al. 2014).

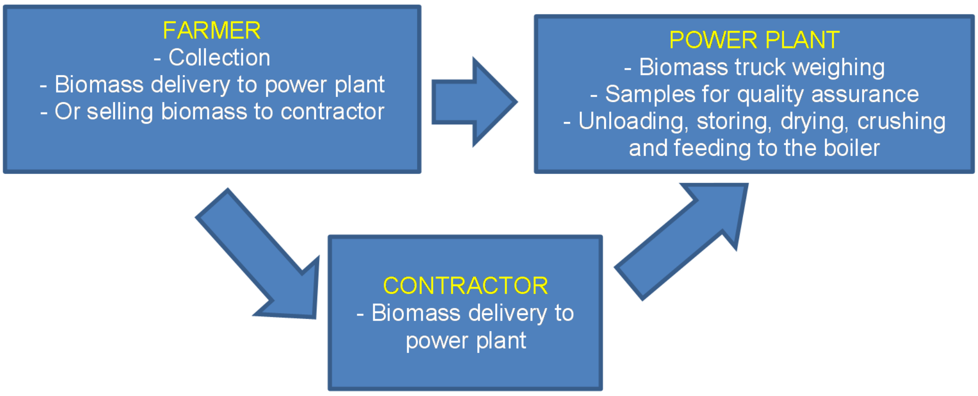


Figure 7. Biomass supply chain to the power plant. (Leinonen et al. 2014)

4.4.2 Harvesting and supply chain of the selected biomass fuels

Prosopis juliflora

Prosopis juliflora is growing free on wastelands, from where it is harvested. License is needed for harvesting from the forest owned by the state. In harvesting of Prosopis juliflora the first phase is to cut the stems. This is typically done manually using an axe. After that, worker delimbs the stems and cuts the tops away. After cutting the stems are piled in small heaps at the harvesting site (Figure 8). Only stems are used for the fuel; tops, branches and leaves are used as a fodder for the cattle.

Figure 8. Harvesting of Prosopis stem for fuel; manual cutting by axe (left), stem fuel (middle) and branches for fodder of animal (right).

Coconut fronds

Coconut fronds are the stiff mid-ribs (stem) of the coconut leaves. Roughly 173 coconut trees are planted on one hectare of land. Each tree gives approximately 12 coconut fronds per year (1 frond per month) each weighing 6–8 kg (wet basis). The annual yield of coconut frond is 14–18 wet tons per ha per year. The initial moisture content of coconut frond is 50–60 wt-%.

The coconut fronds are separated from the leaves manually using e.g. an axe (Figure 9). Leaves are used for instance for basket production. After cutting the coconut fronds are collected manually into small heaps at the farm beside the road where they are dried.

Figure 9. Coconut fronds collected in the small heaps at coconut farm. (Photo by Arvo Leinonen)

Plywood residues

Plywood residues are coming directly from plywood factories by trucks. They consist mostly of clean wood but include some plywood pieces.

4.4.3 Biomass supply and handling at the power plant

Transport

After harvesting the farmer or the contractor of the trader will transport the biomass (prosopis juliflora, coconut fronds and plywood residues) to the power plant. In the case study the average transport distance is assumed to be 50 km (one-way). At the moment in Tamil Nadu many types of vehicles are used for biomass transportation: small trucks (2–3 tons payload), big trucks with tipping device (9 tons payload), big trucks without tipping device (12 tons payload) and tractor trailers. In this study Indian Ashok Leyland Ecomet 1214 truck was assumed to be used. The total weight (load and chassis) is 14 600 kg. The cargo space of the truck is 20.9 m^3 (Figure 10). Loading and unloading of the truck is carried out manually.

Figure 10. Indian Ashok Leyland Ecomet 1214 truck for biomass transport.

Storing

Power plant has a fuel handling yard where biomass is stored, dried and comminuted (Figure 11). The target is to dry the biomass material at the yard up to 40 wt-% moisture content. The material is dried in low layers or in the heaps. It takes several days to dry biomass from 60 to 40 wt-% moisture content when using low layer drying. The fuel layer depth in field drying is approximately 0.6 m. In the heaps it takes one to two weeks to dry biomass down to 30–40 wt-% moisture content. The biomass storages are also used as buffers for the time when there are disturbances in the biomass supply (Leinonen et al. 2014).

Crushing

In the case study Indian stationary RJK-SPWC 75 wood crusher made by Rajukumar Agro Enegineers Pvt. Ltd. was assumed to be used for biomass crushing (Figure 11). The capacity of the crusher is 3–5 tons per hour and the power of the motors is about 67.5 kW. The crusher is equipped with the feeding conveyor. Three men are needed to operate the crusher.

Figure 11. Biomass store yard (left) and crushing unit (right) at power plant. (Photos Arvo Leinonen)

4.4.4 Biomass fuel cost at the power plant

The harvesting and supply costs of different biomass were calculated by summing the working phase costs and other costs. The harvesting and supply costs are presented in €/MWh (Rs/MWh). The harvesting and supply costs are divided for the following cost categories: farmer price, harvesting, road transport, loading and unloading and crushing cost and margin costs. The parameters for the calculation were got during the power plant site visits in Tamil Nadu in 2014 and from the machine manufacturers. The main initial parameters in the calculation are presented in the Table 6.

The loading, unloading and harvesting working phases are carried out manually. The costs (Rs/ton) in these working phases were calculated by dividing the worker's hourly salary (Rs/h) by the productivity (ton/h). The transport and crushing working phases are carried out mechanically. In these working phases the annual costs (Rs/a) were first calculated by summing all the costs consisting of the investment, interest, operation, insurance, overhead and salary costs. The final costs (Rs/ton) were achieved by dividing the annual costs (Rs/a) by annual productivity (ton/a).

In the calculation the costs were first calculated in Rs/ton because the initial parameters were in Rs and tons. After that the production costs were converted to Rs/MWh and finally to €/MWh. In the calculation one € was 84.5 Rs.

Table 6. Initial parameters for the harvesting and supply cost calculation for biomass fuels

Working phase	Parameter	Value
Biomass fuels	Prosopis, LHV a.r., kWh/kg	2.74
	Coconut frond, LHV a.r., kWh/kg	2.55
	Plywood residues, LHV a.r. kWh/kg	3.05
	Cotton stalk, LHV a.r. kWh/kg	2.63
	Prosopis, moisture, wt-%	40.0
	Coconut frond, wt-%	35.0
	Plywood residues, wt-%	35.0
	Cotton stalk, wt-%	40
Farmer price	Prosopis, € (Rs)/ton	10.65 (900)
	Coconut frond, € (Rs)/ton	2.37 (200)
	Plywood residues, € (Rs)/ton	13.0 (1100)
	Cotton stalk, € (Rs)/ton	10.65 (900)
Harvesting	Prosopis, capacity, ton/h	0.19, 0.19
- Cutting and piling	Coconut frond, capacity, ton/h	0.27, 0.27
	Cotton stalk, capacity, ton/h	0.21, 0.21
Transport	Truck	Asho Leyland Ecomet 1214
	Total weight, kg	14 600
	Cargo space, m^3	20.9
	Life time, years	7
	Price, € Rs)	16 805 (1 420 000)
	Transport distance, km	50
Loading - All biomass	Capacity, ton/one man	1.5
Unloading - All biomass	Capacity, ton/one man	2.5
Storing and crushing	Crusher	RJK-SPWC 75
	Capacity, ton/h	3.0
	Power demand, kW	67.5
	Life time	7
Other	Worker's salary, €/h (Rs/h)	0.59 (50)
	Supervisor's salary, €/h (Rs/h)	1.18 (100)
	Interest rate, %	6
	Diesel price, €/l (Rs/l)	0.72 (61.1)
	Electricity price, €/kWh (Rs/kWh)	0.062 (5.27)
	Working time	Two shifts
Profit margin		7.5 % from the total costs

The results from the calculations are shown in Table 7. The most expensive biomass fuel is prosopis juliflora, 9.7 €/MWh (2246 Rs/ton). The cheapest fuel is coconut frond, 6.1 €/MWh (1315 Rs/ton). The supply costs of plywood residue is between these two fuels, 7.3 €/MWh (1855 Rs/ton). The calculated supply costs of different biomass fuels are near the prices in practice in Tamil Nadu in 2014.

The main share of the total costs of prosopis juliflora and plywood residues is coming from the farmer/mill price, 40 % and 58 % respectively. Harvesting is the most expensive working phase in coconut frond supply chain making up about 28 % of the total costs. Harvesting has also a marked impact on the prosopis juliflora supply cost (24 %). The next most expensive working phases in all biomass fuels are transportation and crushing.

Table 7. Calculated biomass supply costs at the power plant gate (€/MWh) in the Case I

€/MWh	Farmer or mill price	Harvesting	Transport	Load& Unload	Crushing	Profit margin	TOTAL
Prosopis juliflora	3.89	2.31	1.30	0.23	1.26	0.73	**9.7**
Coconut fronds	0.93	1.70	1.39	0.25	1.35	0.46	**6.1**
Plywood residues	4.27	-	1.17	0.21	1.13	0.55	**7.3**

4.5 Interactive tool for Case I

In the interactive tool, the economics of the Indian and Western technology plants is compared. The tool for consists of six tabs:

1) Basic info

2) Profits

3) Profits vs. El price (profits as a function of electricity price)

4) Cost of electricity

5) CoE vs Bio price and (cost of electricity as a function of biomass price)

6) Payback

whose contents are shown in Figure 12. Each value having this figure is user-adjustable:  (spinner).

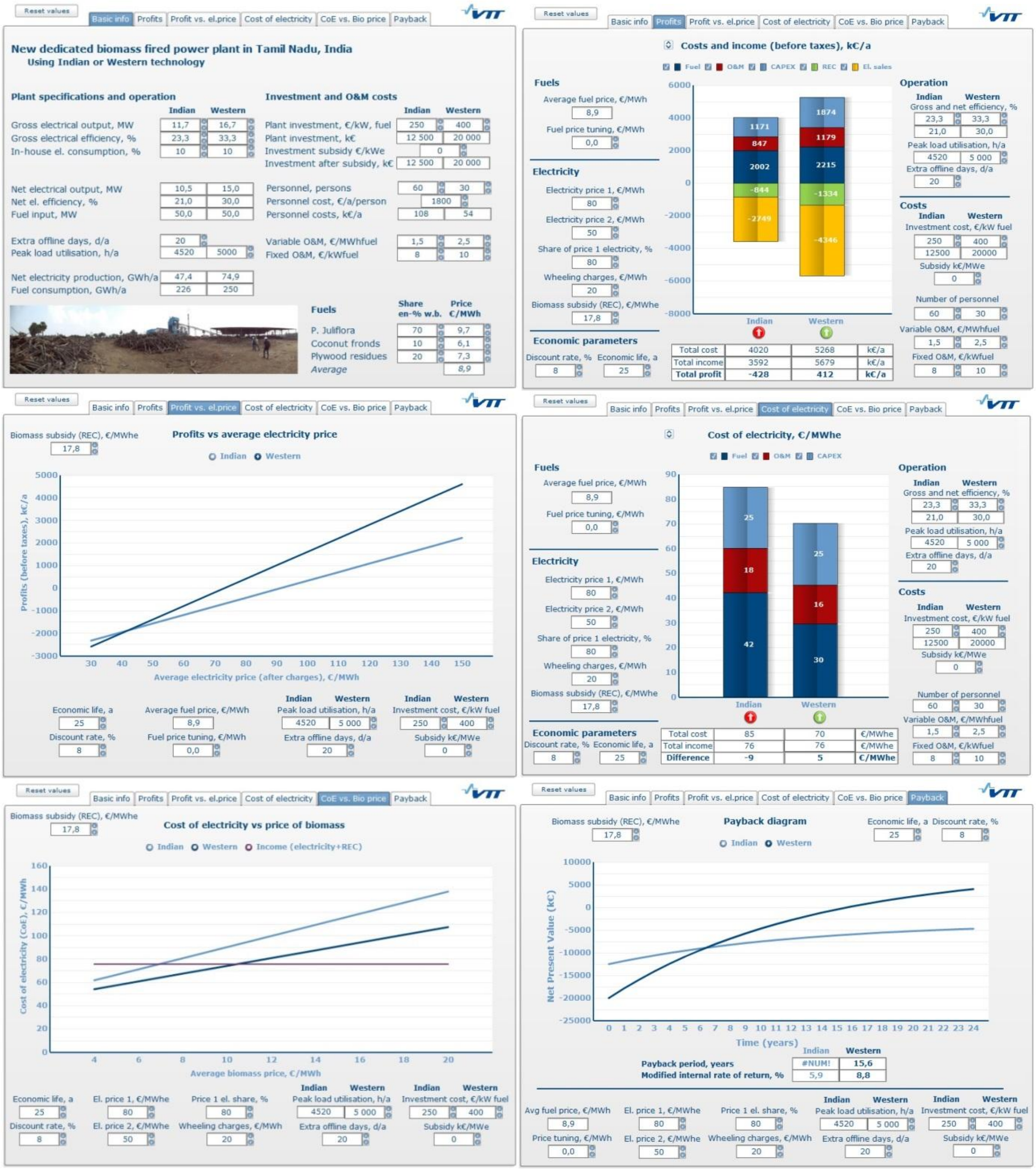


Figure 12. *Snapshots from the developed interactive economic tool for a dedicated biomass condensing power plant feasibility.*

In *Basic info* tab user can specify various plant and fuel related parameters such as capacities, efficiencies and costs.

Profits tab presents the costs and income structure of the plants and as a a difference, also the annual profit/loss before taxes. Many of the parameters found in the Basic info tab can be changed directly from Profits tab also. In addition there are market related parameters such as electricity prices and RECs that can be varied.

The figure in “*Profits vs El. price”* tab illustrates how the electricity price affects the total annual profit/loss.

In “*Cost of electricity*” tab electricity generation costs and their structure are shown on €/MWh basis.

“*CoE vs Bio price*” demonstrates how biomass price affects the cost of electricity. Average price obtained for the sold electricity to governmental grid and to industry (after wheeling charges) is shown as vertical line. CoE must be below this level for the project to be profitable.

In the “*Payback”* tab, a simplified payback diagram and payback periods are shown. Cash flows were assumed to remain the same as for the first operational year for the whole project lifetime in real terms (inflation compensated). NOTE: taxes are not taken into account which makes the results overly optimistic.

In addition to payback periods, modified internal rate of returns (MIRR) for each case are also shown. While the more common financial key figure, internal rate of return (IRR), assumes that the cash flows from a project are reinvested at the IRR, the MIRR assumes that positive cash flows are reinvested at the firm's cost of capital which in this case is the same as the discount rate. Thus, it can be argued that MIRR reflects the profitability of a project more accurately, although it is partly a matter of opinion.

4.6 Main results

Using the default values for the input parameters, the calculated costs of electricity were 85 and 70 €/MWh for the Indian and Western technology plants, respectively (Figure 13). The total income for both cases is ~76 €/MWh of which is ~58 €/MWh comes from electricity sales and 17.8 €/MWhe from RECs. Thus Western technology plant is estimated to be able to generate a profit of ~5 €/MWh when the Indian technology plant would operate at a loss of ~9 €/MWh. So in this case, the higher efficiency of the Western technology boiler more than compensates the higher costs.

By playing with the variables, one can see that to achieve the break-even point (costs equal to income) for the Indian technology plant, one would need for example:

1) Investment cost to decrease from 12.5 to ~8 M€ OR

2) Average biomass price to drop from 8.9 to ~7 €/MWh OR

3) Peak load utilisation to increase from 4520 to ~6000 h/a.

This example demonstrates the usefulness of the interactive tool approach.

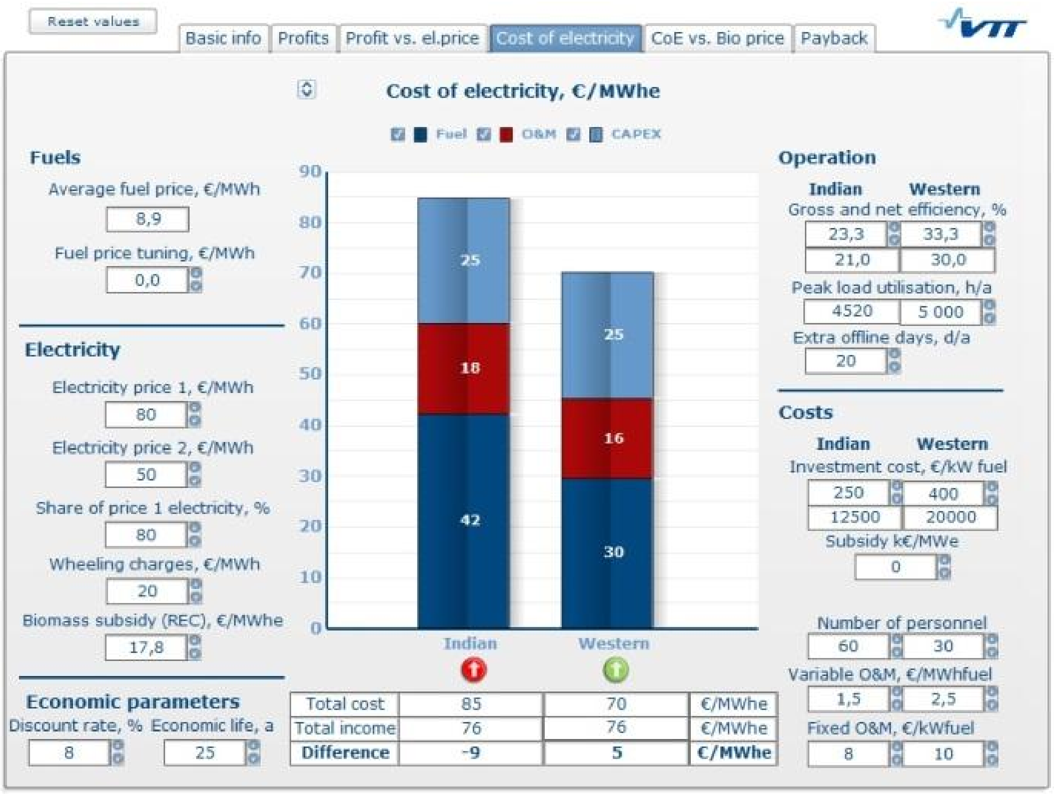


Figure 13. Calculated cost of electricity using the reference values.

It is important to note that without the REC income, the Western technology plant would be clearly unfeasible too even if slightly higher price could then be obtained for the electricity sold to distribution company. REC markets do not seem to be working very well in India as there are a lot of unsold credits as illustrated in Figure 14. This makes the investments relaying on REC income risky.

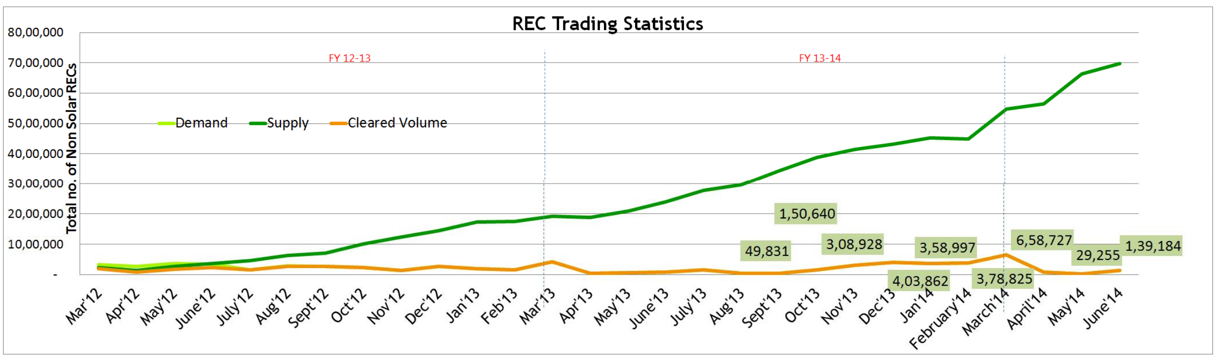


Figure 14. Non-solar REC trading statistics. (REConnect Energy Solutions 2014)

5. Case study II – CHP plant co-firing coal and biomass

5.1 General description

The purpose of the case study II was to evaluate the feasibility for investing into a greenfield multifuel 152 MWth CHP plant producing electricity to grid and steam for industry. The fictional plant was thought to be located in Tamil Nadu and it would co-fire agro and woody biomass with imported coal. Plant could also co-fire domestic, low quality coal with high ash content. Domestic coal is cheaper than imported coal but it has the same challenge as biomass regarding availability and security of supply and challenging combustion quality.

Co-firing biomass (or domestic coal) with imported coal can be seen as a potential way to cope with many challenges as coal secures the fuel supply and keeps the biomass prices under control as the plant has the option to choose the most economical fuels. For dedicated biomass power plants, it has many times been the case that fuel prices have quickly been raised after the power plant has been commissioned. The fuel supply security is especially important for CHP plants that must be able to deliver steam/heat according to demand which is usually quite continuous throughout the year. Co-firing biomass with coal also helps to mitigate ash related challenges often prevailing in 100 % biomass combustion, especially in the case of agro biomass. Co-firing is not, however, a common practice in India today.

Agro and woody residues were thought to be collected from the farms to collecting centre where they will be processed into briquettes which are then transported by lorries to the power plant.

Plant capacity and biomass co-firing shares were selected so that the biomass fuel power is 50 MW (the same as in Case study I).

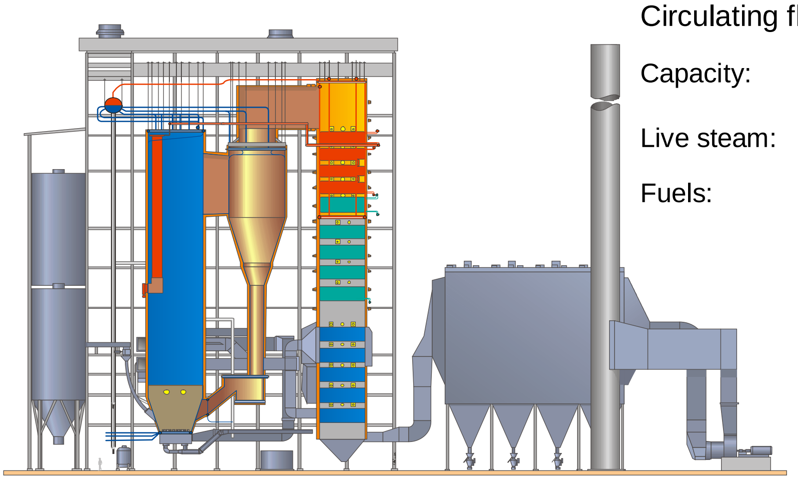
5.2 CHP plant description

The studied plant is equipped with a Circulating Fluidised Bed (CFB) boiler and it can operate on 100 % imported coal or co-fire 30 % (on energy) biomass or Indian coal (Figure 15). Plant provides steam for industries from either 10 or 20 bar extractions from the turbine. Steam turbine has also full condensing mode operation capability. Condenser is water-cooled which decreases the space requirement compared to air cooling (the space available at the industrial parks is a limitation) and increases efficiency.

Steam parameters are 535°C / 115bar / 64kg/s. The boiler was modelled using Aspen Plus simulation software (www.aspentech.com) and it was found that with these parameters, the gross electrical efficiency in full condensing mode is 37 % using 100 % imported coal. In-house electricity consumption was assumed to be 7 % of total gross electrical output leading to a net electrical efficiency of 34.4 %.

Other assumptions:

- Electricity is sold to private industry sites (80 €/MWh) and to governmental grid (50 €/MWh).
- Wheeling charges (20 €/MWh) have to be paid for the electricity sold to private industry sites.
- Plant cannot earn Renewable Electricity Certificates (REC) or other production subsidies from biomass based electricity production since only 15 % annual fossil fuel share is allowed to earn the credits
- Process steam price is 20 €/MWh
- There is natural gas fired back-up boiler at the site to ensure continuous steam production throughout the year (operated for 28 days per year)
- The plant equipment is mostly based on western design
- Automation and instrumentation level is relatively high



Circulating fluidized bed (CFB) boiler

Capacity: 152 MW_{th}

Live steam: 535°C / 115bar / 64kg/s

Fuels: 70-100 % Indonesian coal

0-30 % Biomass or Indian coal

Figure 15. CFB boiler. (Picture is courtesy of Valmet Power, specifications have been made by the authors and they do not represent any actual plant)

5.3 Biomass supply chain and costs

5.3.1 Biomass supply chain

The biomass fuels to be used at the plant, were decided to be Prosopis juliflora (50 % energy basis annually), cotton stalks (30 %), and coconut fronds (20 %) based on the availability in Tamil Nadu state. The share of coconut fronds and cotton stalks were limited due to their challenging combustion properties (Table 3).

The CHP plant was planned to be located next to the process steam utilizers at an industrial site. The space at the industrial site for the biomass storage and handling is limited and dusting could pose problems. Thus it was decided that the biomass is supplied in the form of briquettes. The calorific value of the biomass (prosopis, cotton stalk and coconut fronds) briquettes as received is 3.8–4.4 MWh/ton and density about 650 kg/loose-m^3. The corresponding values for biomass chips are 2.6–2.7 MWh/ton and 300 kg/loose-m^3. From these figures it can be seen that the need for the briquette storage space at the power plant is 70 % lower than with the biomass chips. The higher energy density of briquettes also lowers transportation costs.

The fuel supply chain for the selected biomass fuels is illustrated in Figure 16. After harvesting the biomass fuels are transported first to the collection centres located close to biomass sources (5–20 km). There the fuels are processed into the briquettes. Briquetting process consists of several working phases: drying on open field (to 30–40 wt-% moisture), crushing (particle size to <50 mm), artificial drying (to ~15 wt-% moisture), fine crushing (particle size to <5 mm), briquetting, cooling of the briquettes and storing. Moisture content of the briquettes was assumed to be 10 wt-%. The transport distance of biomass to the processing centre in the calculation was 15 km and the transport distance of briquettes from the processing centre to the CHP plant was 50 km.

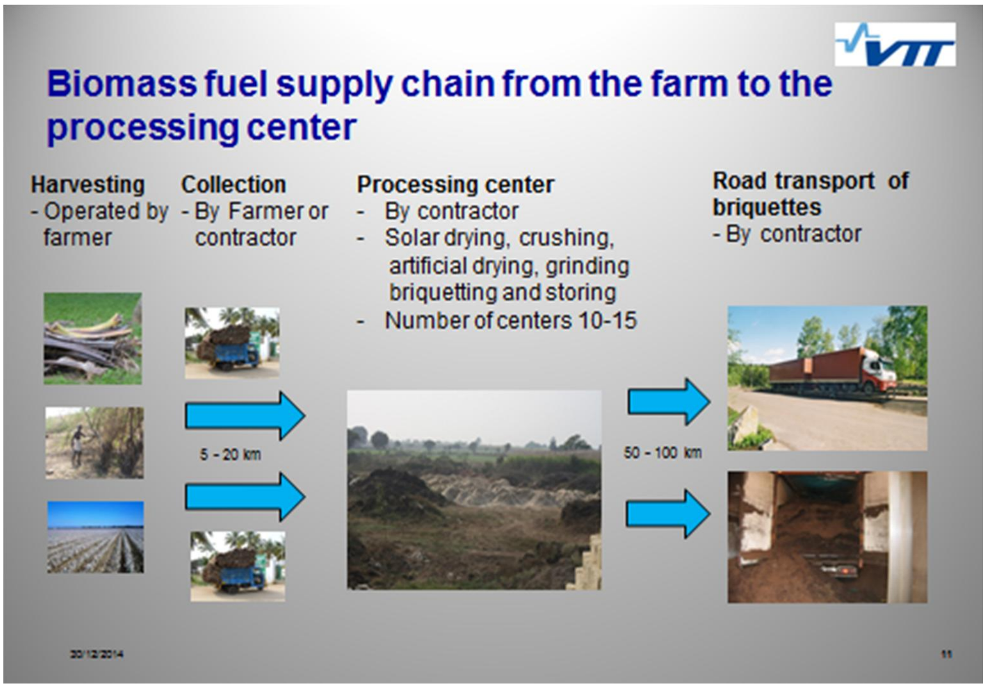


Figure 16. Fuel supply chain for the CHP case study (Case II).

1.1.1 Biomass harvesting and supply and briquetting to the processing centre

The harvesting and supply of prosopis juliflora and coconut fronds to the processing centre is carried out in a similar way as presented in 'Dedicated biomass power plant' case study I (chapters 4.4.2 and 4.4.3). In India cotton is mainly harvested by manual plucking. The harvesting of cotton stalk is also made manually by first cutting the stalk and collecting the stalks beside the road. From the road side the cotton stalk is transported to the processing centre like prosopis juliflora and coconut frond.

At the processing centre the biomass is first dried in the stockpile down to 30–40 wt-% moisture content. In the case study Indian stationary RJK-SPWC 75 wood crusher made by Rajukumar Agro Enegineers Pvt. Ltd. was assumed to be used for biomass crushing like in the 'Dedicated biomass power plant' case study (Figure 11).

After crushing the biomass must be dried to ~15 wt-% moisture content before briquetting. For drying, a flash dryer type FD 5000 manufactured by Indian company Infinite Energy Pvt. Ltd, was assumed to be used. The productivity of this flash dryer is 5 dry tons/h (15 wt-%).

The dried biomass is then fine crushed with a hammer mill (manufactured by Indian company Star Trace private Ltd.) The capacity of the hammer mill is 5–8 tons/h and the grain size after fine crushing is <4 mm.

The fine crushed and dried biomass is briquetted using IB 1000 briquetter (Infinite Energy Pvt. Ltd.). The capacity of the briquetter is 1.25–1.75 tons of briquettes per hour.

Briquettes were assumed to be transported with Indian Ashok Leyland Ecomet 1214 trucks (Figure 10) similarly to raw material transportation.

The main biomass fuel properties as briquettes are listed in Table 8.

Figure 17. Briquetting process.

Table 8. Biomass briquette main properties

Biomass	NCV	Ash content	Moisture content*	NCV as rec*	
	MJ/kg dry	wt-% dry	wt-%	MJ/kg	MWh/ton
Coconut frond	15.45	7.4	10	13.66	3.79
Cotton stalk	17.42	3.2	10	15.45	4.29
Prosopis juliflora	18.04	1.4	10	15.99	4.44

*as briquettes

5.3.2 Briquette cost at the power plant

Calculation method

The harvesting and rough crushing costs of biomass are the same as in the 'Dedicated biomass power plant' case study. The road transport costs of raw biomass to the processing centre are lower than to the power plant because of the shorter distance. The transport distance was 15 km to the processing centre and 50 km to the power plant. The total briquetting costs were calculated by summing up the harvesting, supply and crushing costs with the briquetting and road transport costs of briquettes to the power plant. The briquetting costs consist of fine crushing, drying and pressing costs.

The briquetting costs were calculated in the same manner as the crushing and transport costs in the ‘Dedicated biomass power plant’ case study. The annual fine crushing, drying and pressing costs (Rs/a) were first calculated by summing all the costs consisting of the investment, interest, operation, insurance, overhead and salary costs. The final costs (Rs/ton) were achieved by dividing the annual costs (Rs/a) by annual productivity (ton/a).

In the calculation the costs were first calculated in Rs/ton because the initial parameters were in Rs and tons. After that the production costs were converted to Rs/MWh and finally to €/MWh. In the calculation one € was 84.5 Rs.

The initial parameters of the calculation are presented in Table 6 (harvesting and supply) and in Table 9 (briquetting costs). The initial parameters for briquetting cost calculation have been received from machine suppliers in India.

Table 9. Main initial parameters for the calculation of the biomass briquetting costs

Working phase	Parameter	Value € (RS)
Drying	Flash dryer	Infinite Energy Pvt. Ltd.
	Capacity, ton/h (10 wt-%)	5
	Electricity consumption, kW/h	30
	Number of shifts	2
	Operation time, h/a	3 696
	Number of workers per shift	3
	Biomass fuel consumption, ton/h	0.65
	Price for the dryer, € (Rs)	51 090 (4 317 105)
Fine crushing	Hammer mill	Star Trace Private Ltd.
	Capacity, ton/h (10 wt-%)	6
	Electricity consumption, kW/h	22.5
	Number of shifts	2
	Operation time, h/a	3 696
	Number of workers per shift	3
	Price for the mill, € (Rs)	10 842 (916 149)
Pressing	Briquetter IB1000	Infinite Energy Pvt.. Ltd.
	Capacity, ton/h (10 wt-%)	1.5
	Electricity consumption, kW/h	26.5
	Number of shifts	2.0
	Operation time, h/a	3 696
	Number of workers per shift	2
	Price for the press, € (Rs)	33 880 (93 031 960)
Other	Worker's salary, € (Rs)/a	1.18 (100)
	Supervisor's salary, € (Rs)/a	1.78 (150)
	Manager's salary, € (Rs)	2.96 (250)
	Land price, € (Rs)	118 343 (10 000 000)
	Building costs, € (Rs)	89881 (7 594 937)
	Number of worker's in machine assembling	10
	Number of managers of the plant	3
	Electricity price, € (Rs)	7.7 (650)
	Interest rate	6.0
	Number of supervisors in drying, fine crushing and briquetting per shift	0.5
	Life time of the machines	7

Results from the calculation

The production and supply costs of different biomass briquettes at the power plant gate are shown in Table 10. Based on the study, the cost of briquettes made from cotton stalk and prosopis juliflora is nearly the same; 12.5 €/MWh and 12.1 €/MWh. Using coconut fronds as feedstock the total cost is lower, 9.0 €/MWh.

Farmer price, harvesting and briquetting working phases have the biggest impact on production of briquettes from prosopis and cotton stalks. The most expensive working phases in production of coconut frond briquettes are briquetting, harvesting and crushing.

Table 10. Calculated biomass briquette prices at the power plant gate (€/MWh)

€/MWh	Farmer price	Harvesting	Short transport	Loading + Unloading	Crushing	Briquetting	Long transport of briquettes	Loading + Unloadnig	Profit margin	**TOTAL**
Prosopis juliflora	3.89	2.31	0.58	0.23	1.26	2.46	0.48	0.02	0.91	**12.1**
Coconut fronds	0.93	1.70	0.62	0.25	1.35	2.88	0.56	0.02	0.67	**9.0**
Cotton stalks	4.05	2.16	0.78	0.24	1.31	2.55	0.50	0.02	0.94	**12.5**

5.4 Coal and natural gas

Currently, the state-owned power producers can purchase coal from state-owned Coal India Ltd (CIL) at very attractive price through fuel supply agreements (FSAs). However, the supply is limited and there is constant deficit on availability. Many private players, on the other hand, have to source most of their coal abroad. Indonesia being a common exporter the plant was assumed to use Indonesian coal as the main fuel in this study. A couple years ago Indonesian coal was still cheap. Then there was a change in Indonesian legislation commanding that all the exported coal had to be sold at globally benchmarked prices. This meant radical rise on coal prices for Indian power companies.

Indonesian coal considered in this study was GCV 5200 kcal/kg (as received) quality having ash content of 6.55 wt-% (dry basis) and 22.5 wt-% moisture content (as received). More thorough properties of the coals are shown in Table 10.

Due to shale gas boom in the US, coal prices have declined in recent years and now the FOB price of such coal has been some 50–60 $/ton (7.0–8.4 €/MWh). (Argus 2014) In the study the price for the coal at the power plant gate was assumed then to be 9 €/MWh.

One option to procure domestic coal is through e-auctions, whose purpose is to provide equal opportunity to purchase coal through single window service to all intending buyers. However, there is a dilemma for CIL: they get higher price through e-auctions compared to FSAs but can a state-owned company having a monopoly maximize its profits this way, when there is scarcity on the supply. Due to this reason CIL has agreed to decrease the amount of e-auction coal from 10 to 7 % of its projected sales. (Livemint 2014)

The properties of the domestic coal considered in the study are shown in Table 10. Based on GCV, the domestic coals are classified to grades, G1–G17 and this particular case would be classified to G16. The distinct feature of the domestic coal is the high ash content (41 wt-% dry basis). The price of the domestic coal was assumed to be 6 €/MWh.

Table 10. Coal properties

Analysis	**Unit**	**Indian coal**	**Indonesian coal**
Moisture	wt.-% a.r.	15.0	22.5
Volatiles	wt.-% d.s.	45.0	45.8
Fixed carbon	wt.-% d.s.	14.0	47.6
Ash 815 °C	wt.-% d.s.	41.00	6.55
HHV dry	MJ/kg	13.40	28.07
LHV dry	MJ/kg	12.79	27.02
LHV a.r.	MJ/kg	10.50	20.39
C	wt.-% d.s.	32.4	71.0
H	wt.-% d.s.	2.8	4.8
N	wt.-% d.s.	0.80	1.50
Cl	wt.-% d.s.	0.020	0.010
S	wt.-% d.s.	0.50	0.48
O	wt.-% d.s.	22.5	15.7

Natural gas is needed for the backup boiler. Price of the domestic natural gas is controlled by the state and the price from November 1, 2014 onwards is set at $5.61 per mBtu which accounts for 15.5 €/MWh (1 € = 1.24 $, November 11th 2014). (Business Standard, 2014) Similarly to domestic coal, there is a deficit on domestic natural gas supply in India. If the plant would have to rely on imported LNG (Liquefied natural gas), whose price is determined on the international markets, the price would be some 40–50 €/MWh.

5.5 Summary of the CHP case assumptions

The most relevant assumptions for the CHP case are summarised in Table 11 and Figure 18.

Table 11. Summary of the most relevant default parameters for the CHP case

Multifuel CHP plant	**Value**
Combustion technology	CFB
Thermal power, MW	152
Electrical efficiency, net, % - Condensing mode - Maximum process steam (10 bar) mode	 36.6–37 %* 22.4–22.6 %*
Net electricity output, MW - Condensing mode - Maximum process steam (10 bar) mode	 56.8 33.0
Process steam (10 bar) output, MW	0–111.5
Peak load utilisation, h/a	6500
CAPEX & OPEX & Labour	**Value**
Specific total investment cost €/kWth	440
Total investment cost, M€	66.8
Variable O&M, €/MWh_{fuel} - Indonesian coal - Indian coal - Biomass	 0.8 1.8 1.2
Fixed O&M, % of investment	2.5 % of CAPEX
Number of persons (full time / part time)	80/60
Personnel costs €/a/person	1800
Fuel prices at the gate	**Value**
Indonesian coal, €/MWh (NCV_{ar})	9.0
Indian coal, €/MWh	6.0
Biomass briquettes - Prosopis juliflora, €/MWh - Coconut fronds, €/MWh - Cotton stalks, €/MWh	 12.1 9.0 12.5
Natural gas, €/MWh	15.5
Backup boiler	**Value**
Operating days per year	28
Specific investment, €/kWfuel	125
Efficiency (fuel to steam), %	80
Market parameters	**Value**
Electricity price, €/MWh (industry/governmental grid)	80/50
Wheeling charges, €/MWh	20
Biomass REC, €/MWh	0
Steam price, €/MWh	20
Economic parameters	**Value**
Discount rate, (real terms)	8 %
Technical lifetime, a	25

*depending on the fuel mix

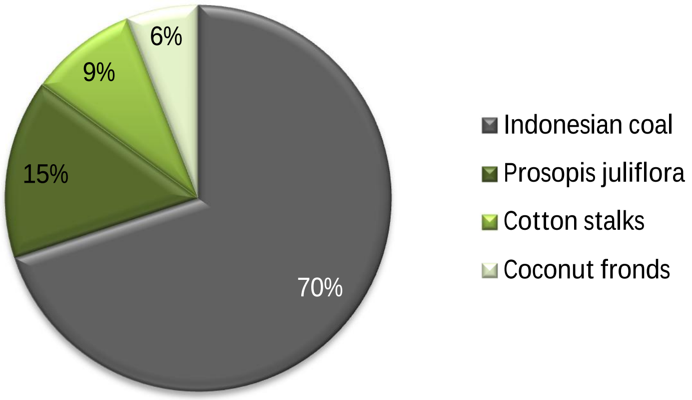


Figure 18. Default annual fuel mix (energy basis) for the biomass co-firing case.

5.6 Interactive tool for the CHP case

In the developed interactive tool, CHP plant operation on three different fixed fuel mixtures is compared:

- 100% Indonesian coal
- 70/30% Indonesian coal and biomass (=50 MW_{fuel} biomass)
- 70/30% Indonesian coal and Indian coal

In addition, a coal-fired condensing power plant is used as the reference. This plant has the same parameters (efficiency etc.) as the multifuel plant in full condensing mode with 100 % Indonesian coal but the investment cost is lower as there is no need for process steam equipment or capability of using biomass or lower quality Indian coal.

One of the main goals for the tool was to allow studying, how the amount of the process steam extraction affects the electrical output and thus the economy of the whole plant. The tool was to allow choosing between 10 or 20 bar steam.

<u>Detailed tool description</u>

The tool consists of five tabs: 1) Basic info 2) Input 3) Biomass fuels 4) Profitability 5) Payback.

In the *Basic info tab (*Figure 19*)*, the outputs, efficiencies, annual production and fuel consumption are shown for each case. Every parameter having this figure is user-adjustable:  (spinner).

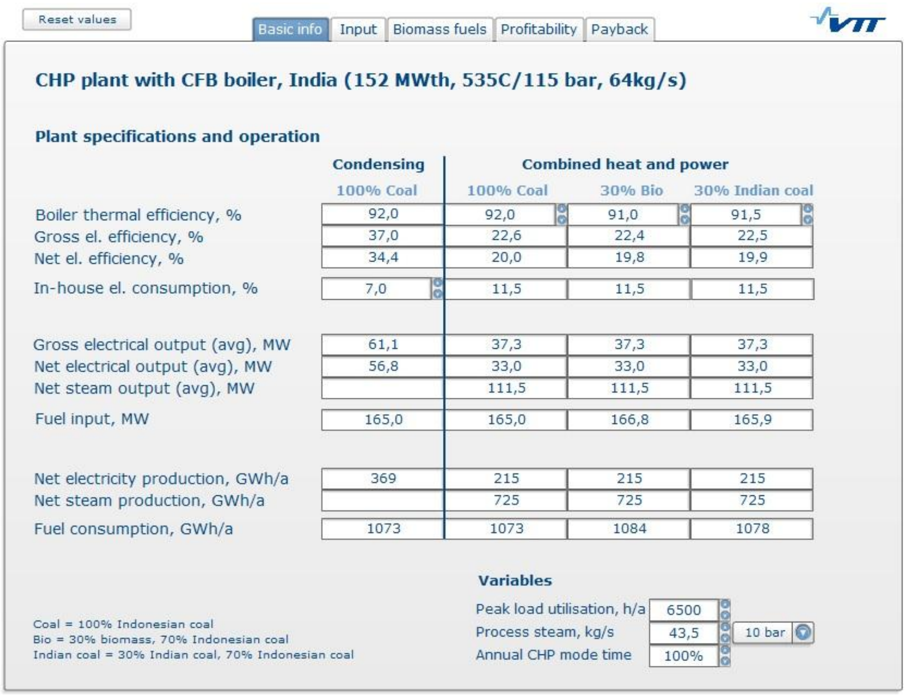


Figure 19. Snapshot from Basic info tab.

As boiler efficiency is dependent on the fuels used, user can specify it for each fuel case. Default boiler efficiencies are 92% / 91.5% / 91% for 100% coal / 30% Indian coal / 30% biomass cases. Boiler thermal output (MWth) remains the same in each case: possible decrease in boiler efficiency in co-firing cases is compensated by higher fuel consumption as shown in Figure 19.

The default value for in-house electricity consumption is 7 % of the gross power output in the condensing mode case. The same absolute value (in MW) is then used for every case.

The user can change process steam production with two variables: 1) Amount of process steam extraction in kg/s (and whether it is 10 bar or 20 bar) and 2) Annual CHP mode time. The amount of process steam in kg/s can be used to study, how the process steam extraction rate affects the electrical output of the boiler and how this in turn affects the economic performance. It is also used to size the backup boiler so it should be considered as a “design spec”.

“Annual CHP mode time” then represents the share of time boiler is operated on CHP mode at the previously specified process steam extraction mass flow rate. Rest of the operation time is condensing mode operation. Thus, the “Annual CHP mode time” parameter is useful for example when there are periods where there is no steam demand but the CHP plant still operates at condensing mode at those times.

The *Inputs tab* (Figure 20) includes various economic parameters such as investment and O&M costs, economic lifetime of the plant and discount rate. There are separate investment costs for condensing coal fired reference case and for the multifuel CHP plant because as mentioned before, the former one is simpler and thus cheaper.

Variable operation costs (without fuel related costs) are given for each fuel separately. The elevated variable operation costs assumed for Indian coal are due to increased ash disposal costs (due to very high ash content).

There is also backup boiler, electricity and biomass share related info that can be changed in this tab.

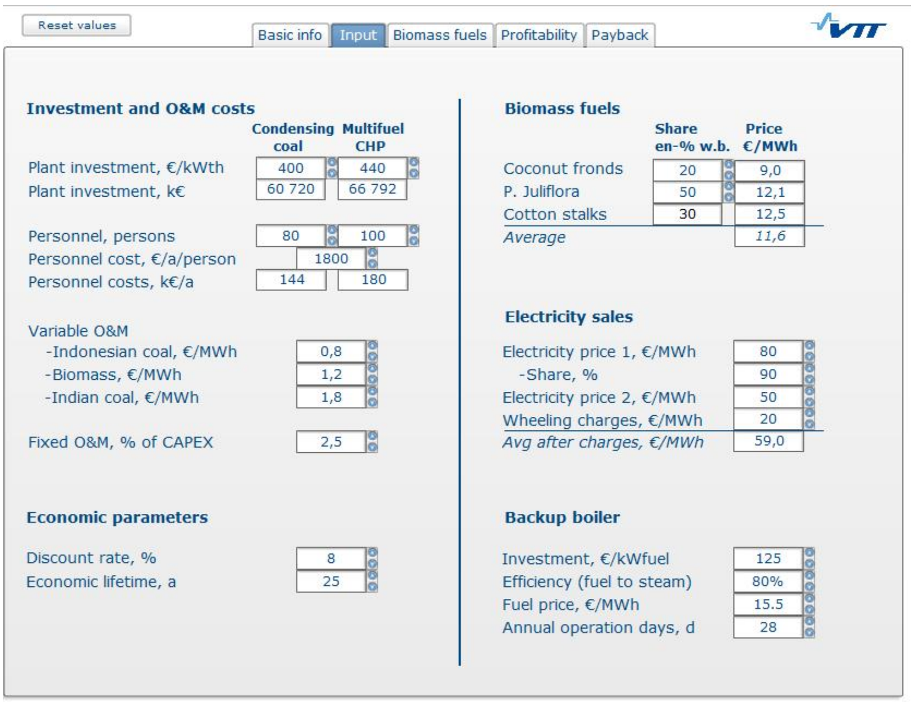


Figure 20.Snapshot from Input tab.

Biomass supply chain calculations were also implemented in the interactive tool with some simplifications in the *Biomass fuels* tab (Figure 21). User has a possibility to change the most relevant parameters such as the price paid to farmer for the raw material, chipping and briquetting costs (per ton basis) and transport distances. Results are then shown on €/MWh basis. By specifying the biomass fuel shares, the average cost for biomass fuels delivered at the power plant gate is shown. Price structures are illustrated in the pie charts.

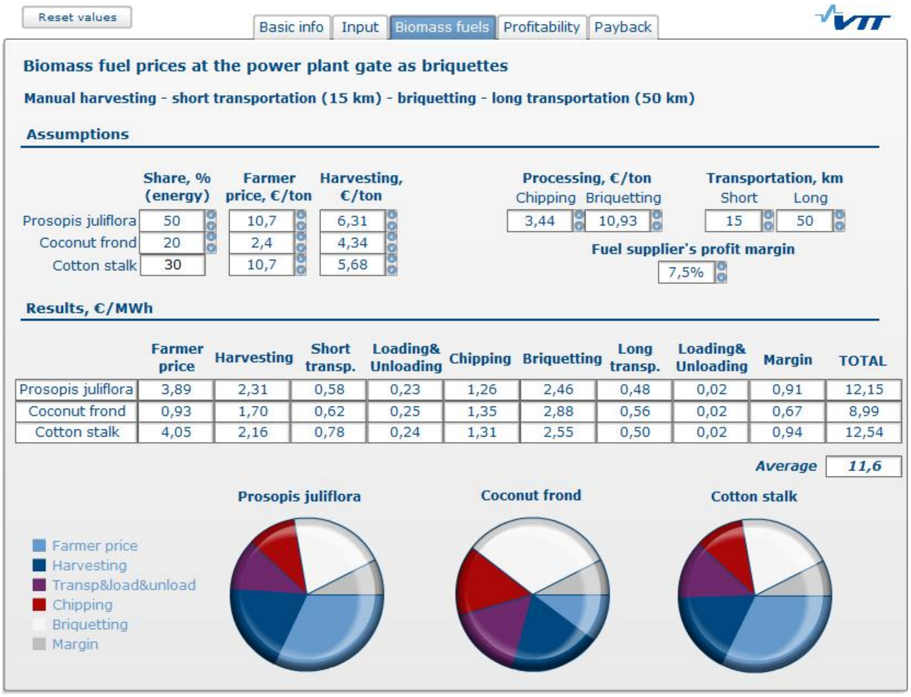


Figure 21. Snapshot from Biomass fuels tab.

Result wise, the most important tab is the *Profitability tab (*Figure 22*)*. The stacked bar charts show costs and income structures for each case. Costs are divided into fuel, O&M, CAPEX and income is from the sold electricity and steam. There is also a possibility to consider Renewable Energy Certificates (REC) as additional income for biomass co-firing case. Today, a plant co-firing 30 % of biomass with coal would not be eligible to REC but it can be used for speculative purposes: what if it would be? Series labelled “Backup” is the lump sum of costs and income from the operation of the backup boiler and thus, it can be either cost or income. In most cases it will of course be a cost.

Below the chart, the total annual cost, income and profit/loss are shown. The relative ranking of the four cases is illustrated by cell background colours.

The most relevant variables can be changed from directly from this tab also so that their effect can be seen more easily.

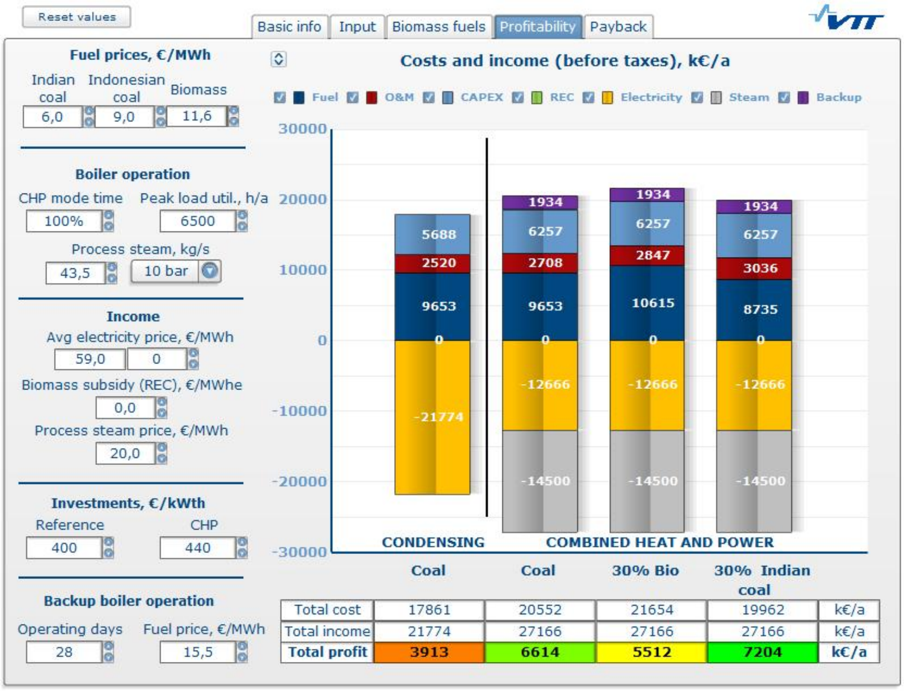


Figure 22. Snapshot from Profitability tab.

In the *Payback tab (*Figure 23*)*, a simplified payback diagram and payback periods are shown. Cash flows were assumed to stay the same as for first operational year for the whole project lifetime in real terms (inflation compensated). NOTE: taxes are not taken into account which makes the results overly optimistic!

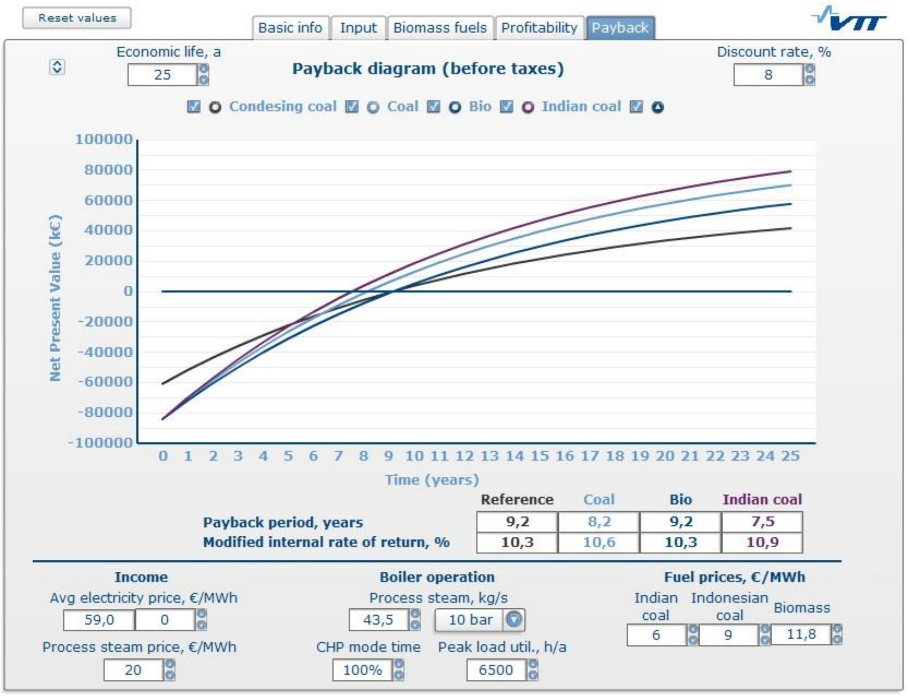


Figure 23. Snapshot from Payback tab.

In addition to payback periods, modified internal rate of returns (MIRR) for each case are also shown. While the more common financial key figure, internal rate of return (IRR), assumes that the cash flows from a project are reinvested at the IRR, the MIRR assumes that positive cash flows are reinvested at the firm's cost of capital which in this case is the same as the discount rate. Thus, it can be argued that MIRR reflects the profitability of a project more accurately, although this is partly a matter of opinion.

5.7 Main results

The most relevant results are shown in Figure 24, where the profitability tab's results are shown using the default values for variables. It can be seen that the most profitable case is the domestic coal co-firing case. As there are no incentives available for biomass for this kind of co-firing case, the use of biomass is not economically viable at the current low coal prices especially if biomass must be delivered as briquettes. If the plant would be able to get Renewable Energy Certificates (RECs) for the bio-based electricity, the 30 % biomass case would become as profitable as the 100 % imported coal case even at the REC floor price of 1.5 Rs/kWh = 17.8 €/MWh. To be more economical than the domestic coal case, the value of RECs would have to rise to >27 €/MWh.

It can also be seen that CHP operation seems to be more beneficial compared to condensing mode operation (Figure 24). The highest profitability is achieved when process steam extraction is set to maximum value 43.5 kg/s (which is also the default value). However, the results are highly dependent on the price of steam as illustrated in Figure 25, where the annual profit/loss is shown as a function of steam price.

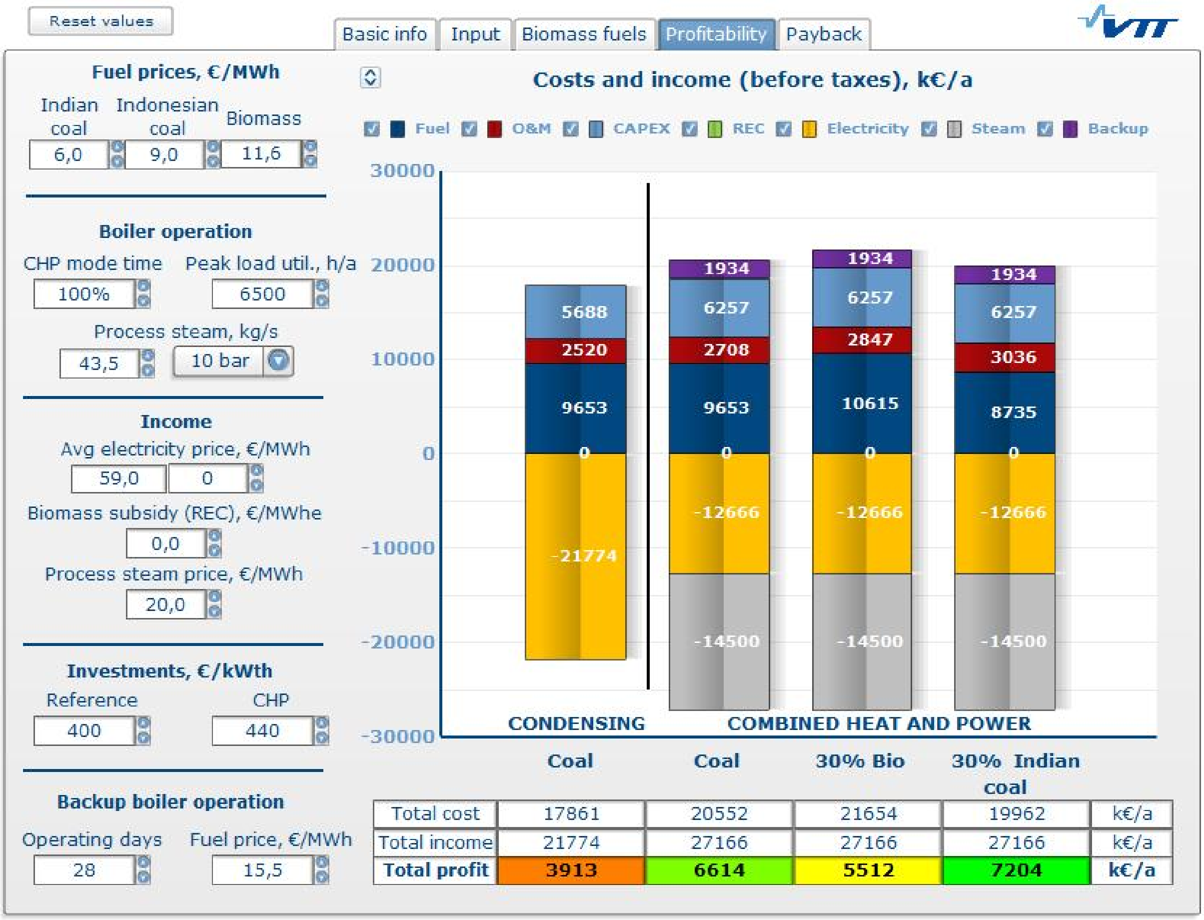


Figure 24. Comparison of the profitability of the different cases.

If steam price drops from 20 to 15.5 €/MWh even the most profitable CHP case (30% Indian coal) becomes less feasible than the reference condensing mode case.

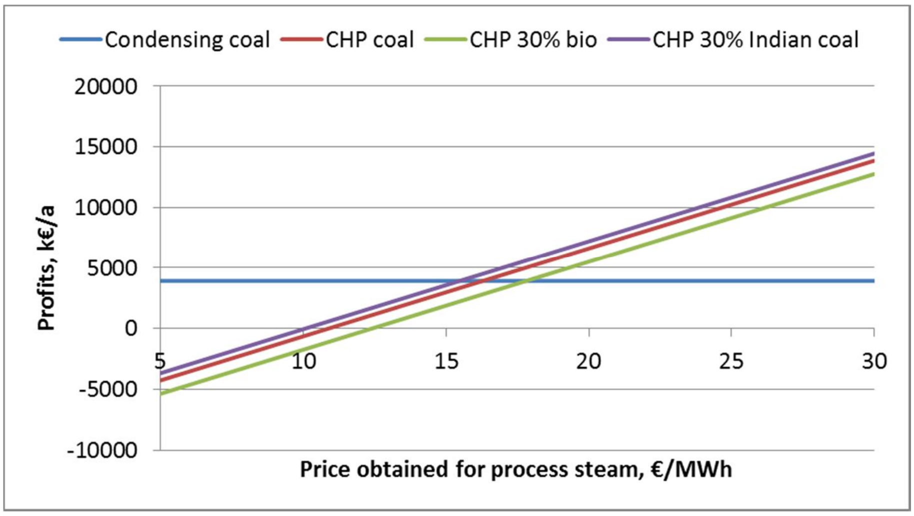


Figure 25. The effect of steam price on profitability of CHP mode operation compared to the reference condensing power plant. (Maximum process steam extraction and 100% CHP mode time assumed for the multifuel CHP plant).

In Figure 26 the effect of the annual continuousness of the process steam need is illustrated. Depending on the fuel case, the plant needs to operate 40–75 % of the time in CHP mode to compensate the higher costs compared to the reference condensing mode case.

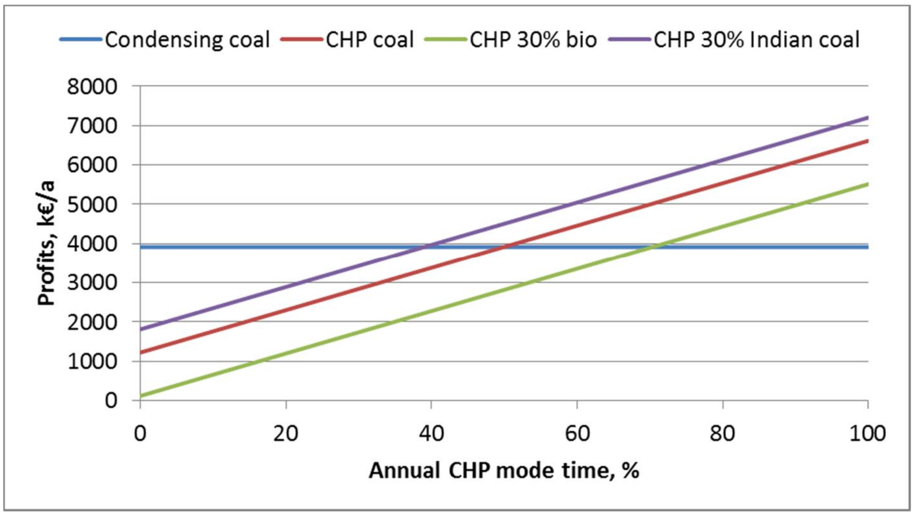


Figure 26. The effect of annual CHP mode time (% of total operation time = CHP+Condensing mode time) on profitability. Steam flow (kg/s) is at maximum value when in CHP mode.

6. Summary and conclusions

Two case studies for evaluating the feasibility of biomass use in energy production in India were carried out. The first study considered investment in to a new dedicated biomass power plant. Two alternative technologies were compared. The first option was “Indian technology” characterised by low electrical efficiency, low level of automation but also low investment and operation costs. The other option was to have a more “Western approach” with higher efficiency and automation level with the drawback of higher costs.

In the second study the feasibility of a multifuel CHP plant capable of condensing mode operation was considered. Operation on different fuel mixtures, consisting of Indonesian coal, biomass and domestic coal, was studied as well as operation on CHP and condensing modes. In this case, the biomass fuels were considered to be briquetted.

In the studies, biomass raw materials were first selected based on their availability and actual use in the selected state, Tamil Nadu. Then the fuel supply chains were specified and the costs of each phase were calculated leading to a biomass price at the power plant gate for each biomass type.

At the end-user site, the studies considered e.g. combustion technology, boiler specifications, plant operation, investment and O&M costs, electricity prices and subsidies. Using the biomass prices and all the other relevant data, the overall economic feasibility was then evaluated. Rather than presenting results only at some fixed parameters, interactive toolkits, which allow the user to study the effects of each variable, were developed.

In the dedicated biomass cases, only the Western technology plant was found to be feasible: the higher efficiency more than compensated the higher costs in this case. Without subsidies the Western technology plant would have been unfeasible too.

In the case of multifuel CHP plant, CHP production was found to be favourable compared to condensing power production although this was found to be highly dependent on the price obtained for the process steam. Of the studied fuel mixtures, co-firing of cheap domestic coal with imported coal was found to be the most economical option. Using biomass in co-firing was not attractive as there are no subsidies available and because briquetting further increased the already high price of biomass. If the plant would have been qualified to obtain Renewable Energy Certificates for the biomass based electricity portion, co-firing of biomass would have been equally profitable as using 100% imported coal.

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