Heat integration opportunities in an average Scandinavian fine paper mill: model study and comparison with a market pulp mill

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ABSTRACT: The pulp and paper industry has a potential for significant energy savings, as shown by many studies on both market pulp mills and integrated pulp and paper mills. In this study, we compare the opportunities for energy savings through heat integration in the two mill types. To do this systematically, we used model mills with an identical pulp mill connected to either a pulp dryer or to two paper machines. An energy analysis of the integrated mill showed that there are steam-saving opportunities of about 16%, which enable increased electricity production or fuel savings in the form of reduced bark burning. For electricity production, the break-even electricity price was 25–50 €/MWh depending on economic conditions. For fuel savings, the break-even bark price was 5–11 €/MWh depending on economic conditions and electricity price (the electricity production decreased when fuel was saved). When comparing the integrated pulp mill with the market pulp mill, the authors identified inherent differences that influenced the steam-saving opportunities in favor of the market pulp mill, implying a payback period about 0.4 years longer in the case of electricity production in the integrated mill. In the case of fuel savings, however, the integrated mill would have significantly better profitability, because fuel savings in the market pulp mill had to be in the form of lignin extraction from the black liquor, which would entail additional investment and operating costs.

Application: By understanding the reasons for differences in steam-saving opportunities between different types of mills, papermakers can develop general guidelines for the best solution for each mill type.

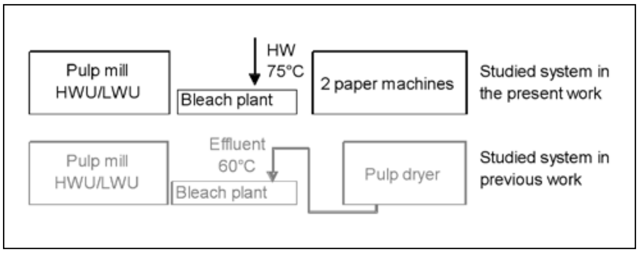
With increasing concerns about fossil CO_2 emissions and rising energy prices, energy savings in energy-intensive industries become ever more relevant. One industry with potential for significant energy savings is pulp and paper production [1]. Previous research done in the authors' department has shown that market kraft pulp mills can reduce their steam demand by 20%–30% [2,3] through improved heat integration and installation of new equipment. Heat integration studies on integrated pulp and paper mills can also be found in the literature [4,5] and show potential for energy savings of about 13%. However, the difference in heat integration opportunities between an integrated mill and a market pulp mill has not been systematically investigated in a thorough way.

The aim of this paper is to identify the inherent differences between a market pulp mill (MPM) and an integrated pulp and paper mill (IPPM) and to determine how the differences influence the heat integration opportunities and the profitability for energy savings. To proceed systematically, computer models of an integrated mill and a market pulp mill were used. In the models, the pulp mills were identical, but the subsequent processes were different. In the MPM, the pulp mill was connected to a pulp dryer, whereas the IPPM pulp mill was connected to two paper machines (PMs). Previous work by the authors investigated the heat integration opportunities in the MPM [2,6]. If the pulp dryer is replaced with PMs, the heat integration opportunities change. Besides the difference in equipment, the energy systems of the two mills also differ, which may influence the profitability of energy-saving projects. Further discussion of the differences in mill conditions can be found in the next section. In the subsequent section, the resulting heat integration opportunities for the IPPM are presented, as well as a comparison with the MPM. After this, the profitability of different uses of the saved steam is presented. In the final section, conclusions are drawn.

The work presented here is based on previous work of the authors [2,6] as well as the Master's thesis of Åsa Stenberg and Asif Mehmood Iqbal [7] (who were supervised by the authors). In these publications, more details about stream data, the approach used, and the heat integration opportunities available can be found.

MILL DESCRIPTION AND COMPARISON WITH THE MARKET PULP MILL

Both the integrated pulp and paper mill (IPPM) and the market pulp mill (MPM) are represented by computer models constructed in WinGEMS [8]. The MPM is a softwood market pulp mill producing bleached kraft pulp, while the IPPM is a fine paper mill. Two different pulp mills with different water consumption were included in the study and connected to the PMs (**Fig. 1**).



1. Description of the systems under study: pulp mills with high and low water usage (HWU/LWU) were connected to a set of two paper machines. In a previous study (gray boxes in the figure), the same pulp mills were connected to a pulp dryer. The pulp dryer effluent can be used in the last washing stage of the bleach plant, while hot water is needed in the bleach plant of the integrated pulp and paper mills.

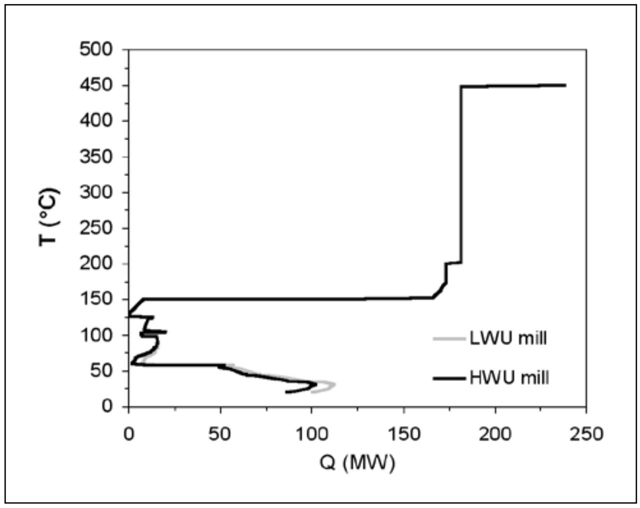
The same pulp mills were previously used with a pulp dryer and analyzed in the same way as in the present study [2].

The models were created to represent typical mills in Scandinavia today as regards equipment and level of resource utilization. Key data for the mills are presented in **Table I**; more details can be found in [7,8]. As can be seen in Table I, the mills are highly energy-efficient compared with international standards [9].

From Table I, some important differences in steam-saving opportunities can be identified. For instance, the consumption of hot and warm water is significantly higher in the IPPM. Increased water consumption generally decreases heat integration opportunities [10]. One reason for the higher water consumption is that the PMs use more water than the pulp dryer. Another is that in the IPPM, the PM effluent is not, for process reasons, used in the last washing step of the bleach plant in the same way that the pulp dryer effluent is used in the MPM (Fig. 1). In the IPPM, hot water, which is warmer than the pulp dryer effluent, is used instead of the effluent. Because warmer water is used in the IPPM bleach plant, the steam demand of the bleach plant is lower in the IPPM. The IPPM also uses less steam for water heating. On the other hand, the steam demand of the PMs is significantly higher than the steam demand of the pulp dryer, resulting in a higher total steam demand for the IPPM. The higher steam demand in the IPPM calls for supplementary firing in a bark boiler. By contrast, no fuel other than the black liquor is needed in the MPM. This difference in energy systems results in different conditions for fuel savings. To reduce the fuel input in the MPM, lignin has to be extracted from the black liquor, which requires investment in a lignin separation plant [6]. By contrast, significant fuel savings can be made in the IPPM by reducing the bark input, which does not imply any additional investments.

	IPPM	MPM
Pulp production (ADt/d)	1000	1000
Paper production (t_{93}/d)	1570	-
Electricity production (MW)	34.5	24.7
ditto consumption (MW)	66.7	33.0
Steam production (MW):	257	201
- Recovery boiler	201	201
- Bark Boiler	56	0
Steam consumption:	257	193
- HP	56	46
- MP	31	33
- LP	170	114
Process water (tonne/Adt):		
- HWU case	35	21
- LWU case	30	14

I. Key data for the integrated pulp and paper mill (IPPM) and the market pulp mill (MPM).



2. Grand composite curve of the integrated pulp and paper mill with both low and high water usage in the pulp mill (HWU/LWU). The minimum heat demand is 238 MW, which is 19 MW less than the original steam demand.

HEAT INTEGRATION OPPORTUNITIES

Pinch analysis

The authors analyzed the heat integration opportunities in the IPPM by using pinch analysis [11], using the same approach as in the MPM study [2]. The pinch analysis was done on the whole mill as one unit, but also on the pulp mill and the PMs separately. With a driving temperature difference for heat exchange of about 5°K, the minimum heat demand of the whole IPPM was 238 MW in both the high- and low-water-usage cases (HWU/LWU) (**Fig. 2**). Because the original heat demand was 257 MW, the pinch analysis suggested that there were 19 MW of pinch violations in the IPPM.

In the next step, the authors wanted to investigate the heat integration opportunities in the pulp mill and the PMs separately. When doing this, it is not obvious where the cold streams representing water heating should be allocated. In this paper, all the water was allocated to the pulp mill, because the pulp mill was capable of heating all the water. The resulting minimum heat demand was 151 MW in the pulp mill and 92 MW in the PMs. Adding these two resulted in a minimum heat demand of 243 MW, which was 5 MW more than if the whole

IPPM were treated as one unit. Hence, the theoretical penalty for not integrating the PMs and the pulp mill was 5 MW. The 5 MW of heat integration opportunity between the pulp mill and the PMs was identified as heating of air to the dryer in the PMs with black liquor flash steam from the pulp mill.

Comparison with the market pulp mill

To compare the heat integration opportunities in the IPPM and the MPM, composite curves for both mill types were plotted on the same graph (**Fig. 3**). As can be seen, the composite curves are very similar, which can be explained by the fact that the stream data are, to a great extent, identical. Despite the similarities, the pinch temperatures are different, implying different characteristics of the pinch violations. When comparing the minimum heat demand with the original case (see Table I), it was clear that the IPPM had 19 MW of pinch violations and the MPM 24 MW. Thus, the theoretical steam-saving potential was 5 MW more in the MPM, regardless of the similarities in the composite curves. The higher potential in the MPM can be explained by the fact that use of steam for water heating in the MPM can easily be decreased [2].

Retrofit measures to save steam

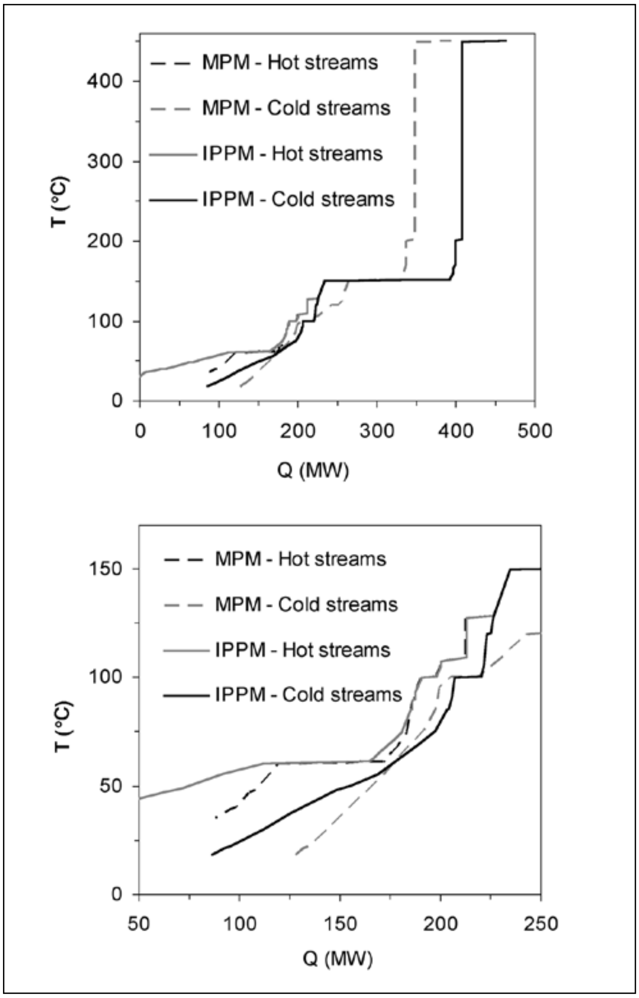
Even though the theoretical savings were the same in the HWU and the LWU cases in the IPPM, it was found that heat integration was more difficult in the HWU case because of the higher water usage. The difficulties of heat integration in the HWU can be anticipated when examining Fig. 3, where the composite curves of the HWU mill are close to pinch around 54°C. The closeness of the composite curves at the low temperature implies that a low temperature difference is necessary for water heating if many pinch violations are solved.

Because of the similarities in stream data in the MPM and the IPPM, one can suspect that the heat integration problem is quite similar in both mills. Indeed, the energy system analyses showed that the retrofit measures used in the MPM [2] could, to a great extent, be applied in the IPPM as well, especially in the LWU case where heat integration was easier. The retrofit measures in the IPPM for the HWU and LWU cases respectively are presented below, and the results are summarized in **Table II**.

In the HWU case, some of the steam from the second black liquor flash could be used for pre-steaming chips, if a chip bin with pre-steaming capabilities were installed. Thus, less steam would be needed in the steaming vessel, and flash steam from the first black liquor flash could be used for preheating white liquor, which would save medium-pressure (MP) steam. Originally, the second flash steam was used for water heating, but the flash steam could be replaced with other heat sources if the hot- and warm-water system (HWWS) were rebuilt with a smaller average driving temperature difference. With a new HWWS, it was assumed that the steam demand for water heating arising from imbalances in the present HWWS would disappear. Moreover, pulp mill effluent could be used for heating in the woodyard, replacing low-pressure (LP) steam for deicing. Finally, exhaust air from the PMs could be used to heat white water. With these measures, about 13 MW out of the 19 MW of pinch violations could be solved.

No heat integration between the pulp mill and the PMs was contemplated. As stated previously, flash steam for heating air to the dryer was the only opportunity for heat integration between these units. For this, a steam reformer and long-distance piping would be needed, and because the flash steam could be used within the pulp mill, this option was discarded.

An additional steam-saving measure was upgrading the evaporation plant. With a modern seven-effect plant with integrated stripper, 22 MW of steam would be saved. With a new evaporation plant, the dry solids content of the black liquor could also be increased from 73% to 80%, increasing the heating value and yielding 6.0 MW more high-pressure (HP) steam. In calculating the investment cost of the evaporation plant, a retrofit situation was assumed in which old equipment could be used to a value of about 8 M€ [2]. For the equipment needed, the same investment costs and calculation approach-



3. Composite curves of the IPPM and the MPM (high-water-usage case for both mill types). Top: the whole system. Bottom: only the part of interest for heat integration. The curves are very similar, implying similar heat integration problems in both mills.

	Steam saving HWU	(MW) LWU	Inv. cost HWU	(M€) LWU
Solving pinch violations:	12.8	15.9	5.2	5.6
-Chip steaming	-	1.9	-	-
-White liquor	6.3	3.7	-	-
-Hi-heat zone	-	3.8	-	-
-Hot water prod*	1.4	1.4	-	-
-Wood yard	1.6	1.6	-	-
-White water	3.5	3.5	-	-
New evaporation plant	21.8+6	21.8+6	6.4	6.4
Tot	40.5	43.8	11.6	12.0

* Due to imbalances

II. Retrofit measures, steam savings, and associated costs.

Heat exchangers	
- Tube and Shell	47907 € + 479 €/m^2
- Air-Water	200 €/m^2
- Air-Air	100 €/m^2
Black liquor flash	1.1 M€
Chip bin	2.2 M€
Evaporation planta	(n·0.86·10^6 + A·333) USD
Pressurized BL tank	1 M€
Back pressure turbine	10.9·MW$^{0.6}$ M€
Condensing turbine	1.96·MW$^{0.6}$ M€

[a] n is the number of effects and *A* the total heat transfer area.

III. Investment costs for equipment needed in the retrofit.

es were used as described in [2,6]. The investment cost values used are summarized in **Table III**.

In the LWU case, less water heating was needed, implying that, in contrast to the HWU case, all steam from the second black liquor flash could be used for pre-steaming. Thus, no LP steam and less flash steam were needed in the steaming vessel. The excess of flash steam could be used for white liquor preheating and in the high-heat washing zone to replace MP steam. To facilitate this operation, a third black liquor flash with higher flash temperature was installed in the model [2]. White water heating, hot water production, and heat to woodyard could be achieved as in the HWU case, giving in total 16 MW of solved pinch violations in the LWU case (Table II). A new evaporation plant with the same steam-saving potential could also be installed in the LWU case.

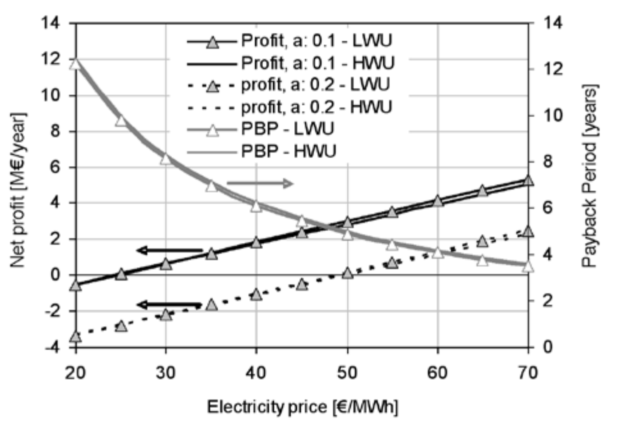
ELECTRICITY PRODUCTION AND FUEL SAVINGS

The steam savings in the IPPM could be used for electricity production or to achieve fuel savings. The potential benefits and investment costs for these two options are summarized in **Table IV**. The two alternatives are further described below, including profitability analyses.

	HWU			LWU		
	MW	%a	M€	MW	%[a]	M€
Steam saving	40.5	16	11.6	44	17	12
Increased electricity prod.	14.2	41	16.2[b]	15	43	16.5[b]
Total cost for retrofit			27.8			28.5
Fuel saving - bark	48.4	70	0[c]	53	77	0[c]
Fuel saving - electricity[d]	-3.5	-10	-	-3.9	-11	-
Total cost for retrofit			11.6c			12[c]

[a] Percent of the total original steam demand.
[b] Cost for new turbines.
[c] No investment cost besides steam savings.
[d] Consequence for electricity production when fuel savings are made.

IV. Potential benefits and costs for increased electricity production and decreased fuel input in the high- and low-water-usage cases (HWU/LWU).

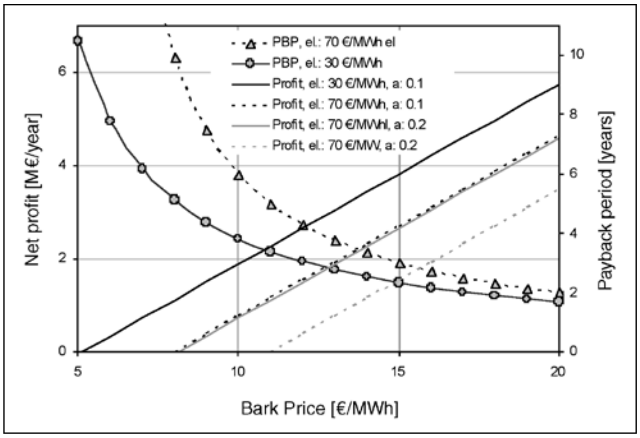


4. Net profit (left axis) and payback period (right axis) for increased electricity production in the LWU and HWU cases as a function of electricity price. Net profits are shown with annuity factors (a) of 0.1 and 0.2.

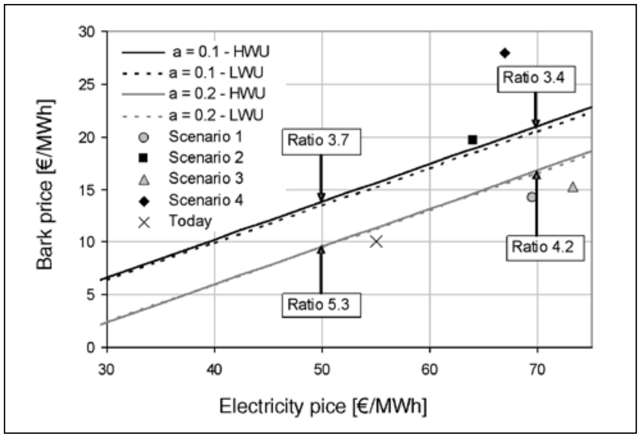
Increased electricity production

The resulting surplus of LP steam could be used in a condensing turbine to produce electricity. Some of the measures also increased the amount of HP steam and decreased the demand for MP steam; excess steam could be used by investing in new backpressure turbines. Investment in new backpressure turbines was also motivated by the fact that the existing ones cannot accommodate all HP steam and some steam has to pass through pressure-reducing valves in the original turbine configuration. With new turbines, the electricity production increased by 14.2 MW and 14.9 MW in the HWU and LWU cases, respectively. The total investment cost for this option was about 28 M€, including steam savings and new turbines.

For the economic evaluation we have used simple payback period (PBP) and the annuity method. With the annuity method the annual net profit from the investment is calculated according to Equation (1). To annualize the investment cost, two different annuity factors (a) were used, 0.1 and 0.2.



5. Net profit (left axis) and payback period (right axis) for fuel savings in the HWU case as a function of bark price. Two different electricity prices were used: 30 €/MWh (solid lines) and 70 €/MWh (broken lines). Net profits are shown with annuity factors (a) of 0.1 and 0.2.



6. Electricity production vs. bark savings. If the intersection of bark price and electricity price is above the lines, bark savings offer higher net profit; if below, the profit from increased electricity production is higher. Energy prices for four future scenarios are included, as well as typical current prices.

The former is based on 5% interest rate (i) and 14.2 years (n), and the latter on 5% interest rate and 5.9 years:

$$\textit{Net profit from investment} = \Delta\ \textit{revenue} - \Delta\ \textit{operating costs} - a \cdot \textit{investment costs} \qquad (1)$$

The profitability of increased electricity production depended on the price of electricity (**Fig. 4**). It is obvious that there was virtually no difference in profitability for the mills with high and low water usage. Moreover, the electricity price had to be over 70 €/MWh to make the payback period come down to three years. This is a high price, but not unrealistic in the future, especially if there are policy instruments promoting green electricity [12]. With the lower annuity factor, corresponding to long-term strategic investments, the annual earnings were positive with an electricity price of only 25 €/MWh. If the higher annuity factor was used, the break-even electricity price was 50 €/MWh.

Reduced fuel input

Instead of producing more electricity in new turbines, the steam surplus offered another opportunity, to decrease fuel input. As stated in the mill description, bark savings can be achieved in the IPPM, and the bark can be sold. When the bark input was decreased to eliminate the whole steam surplus, the electricity production also decreased (Table IV). Hence, the profitability of bark savings depended on both the bark price and the electricity price (**Fig. 5**).

As in the case of electricity production, the profitability was almost the same for the HWU and LWU cases (compare Fig. 4); hence, only the HWU case is presented in Fig. 5. As can be seen in the figure, the break-even bark price was 5–11 €/MWh, depending on the electricity price and annuity factor. As shown in [12], the bark price in the future could be approximately 14 €/MWh or more and the electricity price approximately 70 €/MWh. These prices would give a payback period of less than three years and net profits of 2–4 M€/yr for bark export.

Electricity production vs. fuel savings

The profitabilities of increased electricity production and decreased bark burning are compared in **Fig. 6**. The bark price which gives the same profit for both options is plotted as a function of the electricity price. If the intersection of a bark price and an electricity price is above the lines, the bark saving offers a higher net profit; if below, increased electricity generation is advantageous.

As can be seen in Fig. 6, there was virtually no difference between the LWU and HWU cases. Furthermore, it is clear that electricity production using expensive turbines was promoted by a lower annuity factor. With an annuity factor of 0.1 and with reasonable electricity prices (including the Swedish policy instruments for green electricity), the electricity-to-bark price ratio had to be greater than 3.5–3.7 for electricity production to offer a higher profit than savings on bark fuel. With the higher annuity factor, the critical price-ratio range was wider and higher, 4.2–5.3.

In a previous paper, the authors tried to predict future prices for bark and electricity [12] for the pulp and paper industry. The resulting prices are presented in **Table V**. The electricity prices include policy instruments for green electricity, which makes the electricity price rather high. In Fig. 6, these future prices, as well as a typical price on today's energy market, are indicated. In the future scenarios with high biofuel prices (scenarios 2 and 4), bark savings were preferable. The three other price combinations promoted new turbines. Without the policy instruments for green electricity, bark savings would have been profitable in all scenarios, at least if the higher annuity factor were used.

Comparison with the market pulp mill

In the MPM, more steam savings could be achieved for a lower cost (**Table VI**). As stated above, the difference in steam-sav-

	Prices (€/MWh)		Payback period (years) Electricity		Fuel savings	
Scen.	El.	Biofuel	IPPM	MPM	IPPM	MPM
1	70	14	3.6	3.2	3.1	18
2	64	20	4.0	3.4	1.9	5
3	73	15	3.4	3.0	2.9	15
4	67	28	3.8	3.3	1.2	2.6

V. Payback period for increased electricity production and fuel savings in the LWU case for the integrated pulp and paper mill (IPPM) and the market pulp mill (MPM) for energy prices from four different future energy market scenarios.

	Steam surplus [MW]		Inv. cost [M€]	
	IPPM	MPM	IPPM	MPM
Pinch violations	16.0	17.4	5.6	4.3
New evap. plant	27.8	27.8	6.4	6.4
Blow off	-	8.2	-	0
Total	**43.8**	**53.4**	**12.0**	**10.7**

VI. Steam-saving opportunities and associated costs in the LWU cases of the IMMP and MPM. The LWU cases were used in the comparison because the retrofit measures in these mills are very similar. The MPM had more steam surplus for a lower investment.

ing opportunities arises from the fact that more steam is used for water heating in the MPM. The higher cost in the IPPM was due mainly to a higher heat-exchanger network cost caused by the higher flow rates of hot and warm water. These differences, though, should not have had a detrimental effect on the economic results. However, the resulting steam surplus in the MPM was significantly higher than in the IPPM because the MPM has 8 MW of steam surplus to begin with. Overall, this means that the MPM had about 10 MW more steam surplus available for electricity production or fuel savings, for a 1.3 M€ lower investment.

Because less surplus steam was available at a higher cost in the IPPM compared to the MPM, one could expect lower profitability for increased electricity production and fuel savings in the IPPM. To compare the profitability of the IPPM and the MPM, four different sets of possible future energy prices were used [12] (Table V). As expected, the IPPM had slightly lower profitability in the case of increased electricity production. In the case of fuel savings, however, the IPPM showed significantly better profitability. The reason is that in the MPM the fuel saving requires lignin extraction from the black liquor, which in turn requires a lignin separation plant costing approximately 10 M€ [6] and needing electricity and chemicals for operation.

It should be noted that these results are based on relatively energy-efficient mills. For less energy-efficient ones, the steam-saving opportunities should be greater and the profitability would be different (and most probably higher). This could be an interesting topic for further research.

CONCLUSIONS

The conclusions that can be drawn from the energy analysis of the integrated pulp and paper mill and the comparison with the market pulp mill are as follows:

- There are inherent differences between an integrated mill and a market pulp mill in the areas of steam demand, water usage, and effluent use and flows in the paper machine and the dryer.
- These differences result in fewer opportunities for heat integration in the integrated mill, but the possible steam savings there are still more than 40 MW, or 16%.
- There are no reasonable opportunities for heat integration between the pulp mill and the paper machines.
- Steam savings enable increased electricity production

INSIGHTS FROM THE AUTHORS

The pulp and paper industry, by achieving energy savings in various parts of its processes and a more thorough integration of heat generation and use, could realize significant CO_2-emission decreases to help combat global warming. This energy-saving study goes a little deeper than previous work by identifying the inherent differences in energy-saving opportunities between a market pulp mill and an integrated pulp and paper mill. Model mills were used to ensure a rigorous and fair comparison between the two sets of heat integration opportunities. Although there were a few significant differences between the energy-saving opportunities available in the two types of mill, by and large the opportunities were surprisingly close to identical in both mill types.

The information provided in this paper should be highly useful for strategic planning for energy use and greenhouse gas emission reductions under various economic scenarios. Future work is intended to evaluate the potential for CO_2-emission decrease for the two mill types in various future energy markets.

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which could be profitable with high electricity prices (including policy instruments promoting green electricity). Compared with the market pulp mill, the profitability is slightly less.

- As an alternative to electricity production, fuel savings in the form of bark can be achieved, which provides good profitability with high biofuel price, low electricity price, or both. Compared to the market pulp mill, the profitability for fuel savings is better, because fuel savings in the market pulp mill require lignin extraction from the black liquor, which requires additional investment.

ACKNOWLEDGEMENTS

The work presented here was funded by the Swedish Energy Agency (STEM). The work is a continuation of work initiated in the Swedish national research program, "Future Resource-Adapted Pulp Mill" (FRAM), and good cooperation with units within the FRAM program, especially STFI-Packforsk, has been vital for the preparation of this paper. We greatly thank Åsa Stenberg and Asif Mehmood Iqbal for a fruitful cooperation during the Master's thesis and for their outstanding results that could be used in this paper. We kindly thank Anders Åsblad (CIT – Industriell Energianalys) for his valuable contribution to this work. We also thank Jon van Leuven for editing. **TJ**

Received: April 10, 2007
Accepted: August 15, 2007

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