SIMULATIONS COMPARING CONVENTIONAL EVAPORATION PLANTS WITH PLANTS USING EXCESS HEAT

Marcus R. Olsson[a*] and Thore Berntsson[a]

Pulp and paper mills are large energy consumers which can often achieve economic savings by implementing energy-saving measures. The process unit with the greatest energy demand in a mill is usually the evaporation plant. If excess heat can be made available in the mill, and the heat can be used in the evaporation plant, significant energy-savings can be achieved. In this paper, this kind of energy-efficient evaporation is called process-integrated (PI) evaporation, and the paper investigates the techno-economic consequences of PI evaporation. Theoretical plants with 6–8 evaporation effects are simulated using an in-house simulation tool called OptiVap. Conventional plants are used as reference, and evaporation plants with either lower surface condenser temperature or extraction of lignin are included. The results show that the additional profit of PI evaporation plants is 0.3–1.5 €/ADt in comparison with conventional plants. By lowering the temperature of the surface condenser, the profit is raised by 0.6–0.9 €/ADt for both conventional and PI plants. With lignin extraction, the PI plants are 0.7–1.7 €/ADt more profitable than the conventional ones.

Keywords: Kraft pulp mill; Process-integrated evaporation; Energy efficiency; Energy savings; Low surface condenser temperature; Lignin extraction; Process integration

*Contact information: a: Division of Heat and Power Technology, Chalmers University of Technology, Göteborg, Sweden; *Corresponding author: marcus.olsson@sp.se*

NOMENCLATURE

ADt	Air-dried tonnes of pulp (90% solids)
a	Annuity factor, also called capital recovery factor (1/year), see Eq. 1
BPE	Boiling point elevation
Conv.	Conventional, as in conventional evaporation
eff.	Effects, as in Evaporation effects
Evap.	Evaporation
FRAM	A Swedish national research programme called the “Future Resource-Adapted Pulp Mill”.
GCC	Grand Composite Curve
HP	High-pressure steam; in this study 61 bar(a)
i	Discount rate of an investment, see Eq. 2
LE	Lignin extraction
LLBL	Lignin-lean black liquor
LP	Low-pressure steam; in this study 4.5 bar(a)
n	Economic lifetime of an investment (year), see Eq. 2
PI	Process integrated, as in process-integrated evaporation

PI_1/PI_2	PI evaporation using 1 and 2 GJ/ADt of excess heat
SC	Surface condenser
ΔT_{eff}	Effective temperature difference in an evaporation body; also called the driving force between the condensing steam and the evaporating black liquor.
ΔT_{tot}	Total available temperature difference for an evaporation plant.

INTRODUCTION

Pulp and paper mills are large energy consumers, which can often achieve economic savings by implementing energy-saving measures. The process unit with the greatest energy demand in a mill is usually the evaporation plant, which is a part of the chemical recovery cycle of the mill. By process-integrating an evaporation plant with other parts of the mill, significant energy savings can be obtained in comparison with conventional plants. In this study, process-integrated (PI) evaporation means that excess heat from the rest of the mill is reused in the evaporation plant to reduce the demand for live steam in the plant. The definition of excess heat used here is: heat sources in the pulping process (excluding the evaporation plant) above 80°C but below the pinch temperature (Wising 2003).

The concept of process-integrating an evaporation plant has been described generally by Kemp (1986). This study concentrates on fully integrated evaporation plants, above and below the pinch temperature. Partially integrated plants are not considered, since the discussion is mainly focused on the most energy-saving integration.

Practical examples of PI evaporation in the pulp and paper industry are not common in the literature. No paper was found in which the main evaporation train in a real mill is process-integrated with the rest of the mill. In one of the papers found, Cripps et al. (1996) describe how process integration was used in a real mill to find excess heat and use it in a pre-evaporation train. In that paper, they mention another mill, in which excess heat was already being used in a similar fashion in 1978. That particular evaporation plant was reported to have worked without problems since the start-up. Usage of excess heat in pre-evaporation trains is also described in other papers: Hadwaco Ltd. Oy (2000), Kayser et al. (1998), and Olauson (1979). In these papers, the main source of excess heat was either digester flash steam in chemical pulp mills or steam from grinding in mechanical pulp mills.

Several studies have been made by our research group in which PI evaporation was compared with conventional evaporation. For example, Algehed et al. (2002) showed energy savings of 55% with 7-effect PI evaporation in comparison with a model plant of the best available technology (6 effects). In a comparison with typical evaporation plants in Scandinavia (5.5-effect steam economy), Axelsson et al. (2006a) showed energy savings of 48% by using 7-effect PI evaporation. In the latter example, excess heat of 1.0 GJ/ADt (11.5 MW) at 100°C was available in the mill to save 0.83 GJ/ADt (9.6 MW) of live steam in the evaporation plant.

In our previous studies, the PI plants had a low surface condenser temperature, in addition to using excess heat. In contrast, the present study investigates separately the consequences of using excess heat and of lowering the temperature of the surface condenser. We also compare the consequences of integrating a lignin separation plant (see Section *Lignin extraction*) with conventional and PI evaporation plants. The comparison of conventional plants and PI plants concentrates on differences in required heat transfer surface and steam demand. The study is concluded with a profitability analysis of the two evaporation concepts.

CONDITIONS FOR THE SIMULATIONS

Synopsis of the Conditions

The objective is to compare conventional evaporation plants with PI plants. All evaporation plants are assumed to be greenfield plants, and the study is focused on the profitability of the two concepts. The advantage of PI evaporation over conventional evaporation is a lower demand for steam, whereas the drawback is a higher investment cost (for the same number of evaporation effects). Depending on the value of the steam saved and the extra investment costs necessary, either of the two concepts could be the most profitable.

The study consists of eight simulation cases, see Table 1. Each case is simulated with 6, 7, and 8 evaporation effects, summing up to 24 simulated evaporation plants. These 24 simulations are divided into three groups:

1. **PI evaporation**: Conventional evaporation plants are compared with two examples of PI evaporation plants with 1 and 2 GJ/ADt of excess heat (PI_1 and PI_2).
2. **Low SC**: The temperature of the surface condenser (SC) is lowered to compare the economic gains in conventional evaporation plants with the gains in PI_1 plants.
3. **Lignin extraction**: All cases with lignin extraction are simulated with a production increase of 25%, since previous studies (Axelsson et al. 2006b; Olsson et al. 2006) show that lignin extraction (LE) is the most interesting in connection with an increased production of pulp. As reference plants, conventional plants without LE, but with increased production, are added.

Key Data for the Simulated Evaporation Plants

The assumptions were made that all of the simulated plants are complete plants that are newly installed; thus, no parts of an old plant could be reused. Furthermore, the plants are assumed to be built in a typical, Scandinavian, market pulp mill producing bleached kraft pulp from softwood. This particular mill concept has been developed as a computer model during the FRAM (Future Resource-Adapted Pulp Mill) programme (Axelsson et al. 2006a; FRAM 2005). The aim of the programme was to investigate measures to decrease the environmental impact of pulp and paper production. Central parts of FRAM were to investigate energy efficiency measures.

Table 1. Overview of the Eight Simulation Cases, Divided into Three Groups. All cases are simulated with 6–8 evaporation effects. The evaporation plants are either conventional (Conv.) or PI evaporation plants using 1 or 2 GJ/ADt of excess heat (PI_1 or PI_2). The distinguishing features are underlined.

	PI evaporation			Low SC		Lignin extraction		
	Conv.	PI_1	PI_2	Conv.	PI_1	Conv.	Conv.	PI_1
Pulp production	100%	100%	100%	100%	100%	<u>125%</u>	<u>125%</u>	<u>125%</u>
Surface condenser*	55°C	55°C	55°C	<u>40°C</u>	<u>40°C</u>	55°C	55°C	55°C
Excess heat (GJ/ADt)	0	1**	2^{α}	0	1**	0	0	1^{β}
Extracted lignin (kg/ADt)	0	0	0	0	0	0	<u>292</u> $^{\xi}$	<u>292</u> $^{\xi}$

* Temperature of the condensing steam. ** 11.6 MW $^{\alpha}$ 23.1 MW $^{\beta}$ 14.5 MW $^{\xi}$ 65% solids

We further assume that the solids content of the heavy liquor is increased, from 73% to 75%, while the plant is rebuilt. The limit 75% is a consequence of only using LP steam[1] as live steam in order to simplify the economic calculations. This decision could also be motivated by the assumption that the mill is uninterested in decreasing the electricity production (which would be so when using medium pressure steam).

The evaporation plants in the present study have a counter-current liquor flow. The evaporation capacity is 357, 446, and 478 tonnes of water per hour for the plants with normal production, increased production, and increased production with lignin extraction, respectively. The pulp production of the mill is 327,000 ADt/year (1000 ADt/day).

The Concept of Process-Integrated (PI) Evaporation

In this study, PI evaporation means that the evaporation plant uses excess heat from the rest of the mill to reduce the need for live steam; see Fig. 1. The excess heat can be supplied as steam to the evaporation effect where the driving steam is of the corresponding temperature. On one hand, it is the most energy-efficient to adjust the temperature profile in the evaporation train so that the excess heat is re-used in as many effects as possible. To achieve this, the ΔTs of the effects above the temperature of the excess heat should be as high as is technically possible. Consequently, the other evaporation effects will have ΔTs as low as possible. On the other hand, to promote a low requirement for the total heat transfer area, the ΔT should be similar in the evaporation effects. Depending on the value of the steam and the necessary investment costs, there is a trade-off regarding the optimal ΔT in the evaporation effects.

[1] 75% solids content is a commonly used limit in Scandinavia when only LP steam is used (Olausson 2008).

An alternative way of using the excess heat is to preheat the black liquor between the evaporator bodies. An advantage of this approach can be that the excess steam does not need to be reformed when the steam is not sufficiently clean. Another advantage is that the excess heat can be supplied at a lower temperature and still have the potential to result in the same steam savings. A drawback to this approach may be the difficulty in managing fouling of black liquor in a heat exchanger (Redeborn 2008). This alternative way of using the excess heat is not, however, investigated in this study.

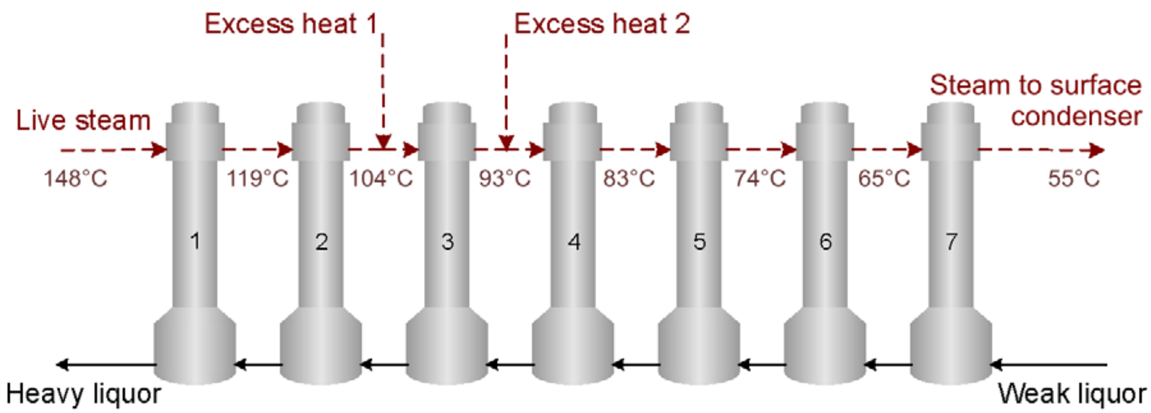

Fig. 1. An illustration of a process-integrated evaporation plant with seven evaporation effects and two temperature levels of excess heat. In this paper, only one temperature level of excess heat is used at a time. Rough temperatures of the condensing steam in the effects are shown to give an idea of the temperature drop in the plant.

The amount of excess heat available at the mill can be assessed by using pinch analysis. Pinch analysis is a method to investigate the minimum heating and cooling load of the mill (Wising 2003) in order to take energy-efficiency measures. In the present study, no pinch analysis is included, but the results from a previous pinch analysis study (Axelsson et al. 2006a) are instead reused. Two amounts of excess heat have been investigated: 1 and 2 GJ/ADt (each PI plant has either of these amounts). The lower amount of excess heat is of frequent occurrence in previous studies, whereas 2 GJ/ADt is added to investigate the difference in profitability with greater amounts of excess heat. The excess heat is assumed to be at 105°C; a sensitivity analysis of the temperature is presented in Section *Sensitivity to the temperature of the excess heat*. Sources of excess heat could be black liquor flash steams, or the primary and secondary condensers of the condensate stripper. In the case of 2 GJ/ADt of excess heat, the smelt dissolver could be an additional source of excess heat.

Furthermore, we have not included any pinch violations in the study. Should pinch violations exist, they may affect the amount of excess heat accessible to the evaporation plant. If so, there is a trade-off between solving pinch violations and extracting excess heat. In this situation, the profitability of the PI evaporation plants depends on which pinch violations that are solved. The conventional plants would probably get a better economy than in the current study, since solving pinch violations is usually profitable.

Lower Temperature of the Surface Condenser

With a lower temperature of the surface condenser, the total available temperature difference in the evaporation plant is increased. Greater temperature differences in the evaporation effects mean stronger driving forces, hence less need to invest in heat transfer surface.

Unfortunately, there are drawbacks to lowering the temperature of the surface condenser. First, a lower surface condenser temperature requires higher investment costs, since the volume flows of the steam are higher in the last evaporation effect(s). To give an idea of the scale, the saturation pressure of steam at 55°C is 0.16 bar(a), whereas it is less than half of that, 0.07 bar(a), at 40°C. Also, the surface condenser has to be larger due to the larger volumes. These additional costs are included here. Second, the temperature of the produced warm water in the surface condenser decreases. This has to be taken into account when designing a new hot and warm water system for a mill. In previous studies (Axelsson et al. 2006a; Axelsson 2008, Paper VI), the amount of warm water was still sufficient, even after lowering the surface condenser temperature.

Lignin Extraction

Purpose of lignin extraction

The purpose of extracting lignin could be to diversify the product mix from the pulp mill by selling the lignin as a biofuel or as a feedstock for chemical synthesis. Another purpose of extracting lignin could be to enable increased pulp production in a mill. An increase in the production of pulp is of economic interest to many kraft pulp mills. However, significant increases in the production generally require costly investments. These investments can be avoided by extracting lignin from the black liquor before it is burnt in the boiler, thus enabling the old boiler to still be in operation.

Method used to separate lignin from black liquor

All data concerning the lignin separation plant originate from experience obtained within the FRAM programme (Delin 2008; Öhman 2008). Lignin is assumed to be precipitated from a portion of the black liquor in the evaporation plant. The liquor is diverted from the evaporation plant at a position where the solids content is about 45%. The pH of the black liquor is lowered by injecting CO_2, which causes the lignin molecules to agglomerate, thus forming a precipitate. The precipitated lignin is separated and then washed with acidified condensate from the evaporation plant. The final lignin cake has a solids content of 65%; the filtrates from the lignin separation plant are recirculated to the evaporation plant.

A production increase of 25% in the model mill studied requires the extraction of at least 292 kg lignin/ADt (65% solids) from the black liquor to debottleneck the recovery boiler (Delin 2008). This corresponds to 35% of the lignin in the weak liquor, or 77,600 tonnes/year (65% solids). It was assumed in the simulations that 292 kg/ADt (65% solids) lignin could be extracted from the black liquor, without going into further details of the consequences for the energy system in the mill.

More information on the lignin separation method applied is available in Olsson (2009, Paper 5).

Consequences for the evaporation plant of extracting lignin from black liquor

When lignin is extracted from black liquor, the evaporation capacity of the plant has to be increased, since filtrates from the lignin separation plant must be evaporated when recirculated to the evaporation plant. This is included in the current study and is described in more detail in Olsson (2009, Paper 5).

Moreover, the physical properties of the black liquor in the evaporators alter when lignin-lean filtrates are recirculated and mixed with ordinary black liquor. Previous research (Moosavifar et al. 2006; Wennberg 1990) shows that the boiling point elevation (BPE) is affected only marginally, and that the viscosity of lignin-lean black liquors (LLBL) is lower than that of ordinary black liquors at the same temperature and solids content.

In the current simulations, the BPE was modelled in the same way as for ordinary black liquor, whereas the viscosity of LLBL was assumed to be 40% lower than that of ordinary black liquor in Effect 1. The figure 40% is based on experiments by Moosavifar (2008) and interpolation (Olsson 2009, Paper 5) to suit the current conditions.

The Simulation Tool

The simulation tool (OptiVap) was originally created in our research group by Algehed (2002) and has been developed further by Olsson. The current version of the tool is described in more detail by Olsson and Berntsson (2007).

OptiVap uses spreadsheets in Excel for steady-state energy and material balances, and functions in Visual Basic for the physical properties of steam and black liquor. Important physical properties include BPE, viscosity and heat transfer coefficients. All of the properties are modeled with equations from the literature. Some practical assumptions were made after discussions with engineers at Metso Power (previously Kvaerner Power) and ÅF-Process during the development of OptiVap.

Economic Conditions

Profitability analysis

In the profitability analysis, the net annual profit from an investment was calculated with the annuity method, see Eq. 1. The Δ revenue and Δ investment are divergences from a reference plant (the difference in operating cost was assumed negligible). This means that the final Δ profit from an investment is the additional profit, positive or negative, compared with the reference plant. The annuity factor (or capital recovery factor), a, has been set to 0.10 based on newly installed plants.[2]

$$\Delta \text{ profit} = \Delta \text{ revenue} - a \cdot \Delta \text{ investment cost } (-\Delta \text{ operating cost}) \quad (1)$$

where

$$a = \frac{i}{1-(1+i)^{-n}} \quad (2)$$

[2] When applying the economic lifetime n = 25 years and the discount rate i = 9% (excluding taxes). (Redeborn, 2008)

The revenue compared with a reference plant was calculated using the resulting steam demands and the value of that steam. Since the value of steam can be calculated in several ways, the profit is plotted versus steam values ranging from 0 to 25 €/MWh. (Estimation of steam values is discussed in Section *The value of low pressure steam*.)

The required investment costs were estimated by an evaporation expert (Redeborn 2008), using the heat transfer areas and number of effects in this work (see Table 2). Redeborn started by estimating the investment cost for the conventional plant with 7 effects, and then used this plant as a reference for the other plants. The costs for the other plants were estimated by assessing the deviations from this reference plant in economic terms.

For the PI evaporation plants, there is an additional cost for making excess heat available to the evaporation plant. This cost is taken directly from Axelsson et al. (2006a): 2.5 M€ for the PI_1 plants with normal pulp production. The costs of excess heat for PI_1, with increased production, and PI_2 are scaled using 2.5 M€ as the basis: 3.1 M€[3] and 5.0 M€[4] , respectively. Investment costs, for piping, pumps and storage tanks which may be necessary for connecting the lignin separation plant to the evaporation plant, are assumed to be the same in all of the plants compared. When the temperature of the surface condenser is lower, the additional costs of higher specific volumes are included in the total investment cost.

The value of low pressure steam

The value of low pressure (LP) steam in a real mill can be estimated in different ways; three possible ways are:

- The value of the fuel that can be saved by not having to produce the steam, as well as the value of the possible decrease in electricity production;
- The income from selling heat produced by the steam (e.g. district heating); and
- The value of electricity that can be produced by the steam in a condensing turbine.

As an example, Reese (2006) states that the value of LP steam[5] was typically 8 €/MWh[6] for American conditions in 2005. In the model mill studied here (FRAM, 2005), the value of LP steam is 8–13 €/MWh provided that:

- All of the surplus steam can be used to produce electricity,
- 1 MWh of LP steam can generate 0.19 MWh of electricity, and
- The electricity price is 40–70 €/MWh.

In real mills, the steam can be valued differently depending on the amount of steam surplus (Towers 2005). For example, if the turbines are run close to their limit, only some LP steam surplus can be used to produce electricity in condensing turbines.

[3] $2.5 \cdot 1.25 = 3.1$ (125% pulp production instead of 100%)
[4] $2.5 \cdot 2 = 5.0$ (2 GJ/ADt of excess heat instead of 1 GJ/ADt)
[5] 5.5 bar(a), originally stated as 65 psi(g).
[6] Originally stated as $5/klb with the given span of $2–$8/klb, equivalent to 3–13 €/MWh. The typical electricity price was considered $40/MWh.

Additional steam surplus cannot be used for electricity production; hence it has a different value.

RESULTS AND DISCUSSION

Steam Demands and Required Investment Costs

The steam demands and required investment costs of the simulated evaporation plants are shown in Table 2 and Fig. 2. Figure 2 predicts, as expected, that the PI evaporation plants will have lower steam demands but require higher investment costs than conventional plants when compared for the same number of effects. On the other hand, when comparing the 7-effect and 8-effect conventional plants with the 6-effect and 7-effect PI plants, respectively, the PI plants both have lower investment costs and lower steam demands. This means that if using a PI plant instead of a conventional plant, a reduced steam demand can be achieved using one less evaporation effect. The lower steam demand for PI plants offers lower CO_2 emissions into the atmosphere, since either less steam needs to be produced or the steam surplus can be used to produce green electricity.

The investment cost of additional evaporation effects increases more for PI plants than for conventional plants. At the same time, the steam demand with additional effects is reduced more (in percentages) for PI plants than for conventional plants. The explanation is that the more effects there are, the greater the share of the effects that can make use of the excess heat. Since the excess heat enters Effect 3 in most of the simulated plants, it is used in 4/6 = 67%, 5/7 = 71% and 6/8 = 75% of the effects for a total of 6, 7 and 8 effects, respectively, see Fig. 1.

For the simulations with a lower temperature of the surface condenser, the savings in investment costs are higher the more evaporation effects there are. This is natural, since the total available temperature difference (ΔT_{tot}) increases more, in percentages, for more evaporation effects. With 8 effects, the steam demand is also lower with a low SC, since it was possible to use the excess heat in one more effect due to the lower surface condenser.

The larger heat transfer surfaces in the PI evaporation plants, compared with the conventional plants (see Table 2), depend on a lower ΔT_{tot} in the PI plants. The lower ΔT_{tot} is caused by a higher BPE, which in turn depends on a higher solids content of black liquor in the evaporators. The solids content is higher because the excess heat causes more water to be evaporated at low temperatures.

Profitability Analysis

Group 1: PI evaporation plants

In Fig. 3, the profitability of conventional evaporation plants (Conv. evap.) is compared with PI evaporation plants for LP steam values ranging from 0 to 25 €/MWh. The economically preferable alternative between 0 and 5 €/MWh is the 6-effect Conv. plant, between 5 and 10 €/MWh the 6-effect PI_2 plant, and above 10 €/MWh the 7-effect PI_2 plant. For steam values above 5 €/MWh, there are always PI evaporation plants which are more profitable than the conventional plants. It is, however, important to keep in mind that the economic results could change if there are pinch violations that compete with the excess heat; see Section *The Concept of Process-Integrated Evaporation*.

For the reasonable span in steam value 8–13 €/MWh (discussed in Section *The value of low pressure steam*), the difference between the highest and the lowest profit is about 1 M€/year. The highest profits were achieved in the PI_2 plants with 6 or 7 evaporation effects. These profits were 0.2–0.4 M€/year (0.6–1.2 €/ADt) and 0.3–0.9 M€/year (0.9–2.8 €/ADt) higher than the profit for the best PI_1 plant and Conv. plant, respectively.

The PI evaporation plants need a higher steam value than conventional plants to motivate 7 or 8 evaporation effects. The limit where 7 effects are preferable over 6 effects is 8 €/MWh for conventional plants, 9 €/MWh for PI_1 plants and 11 €/MWh for PI_2 plants. Eight evaporation effects are probably not worth investing in, at least not for PI plants. For conventional plants with steam values above 13 €/MWh, eight effects might be a good choice.

Group 2: Lower temperature of the surface condenser

The economic consequences of lowering the temperature of the surface condenser are shown in Figs. 4 and 5. For steam values between 8 and 13 €/MWh, the economically preferable alternatives are PI_1 with 7 or 8 evaporation effects. Comparing the profitability (at 8–13 €/MWh) of these plants with the best plants for the other alternatives gives:

- 0.2–0.3 M€/year (0.6–0.9 €/ADt) higher profit than PI_1 evap. with normal SC,
- 0.2–0.5 M€/year (0.6–1.5 €/ADt) higher profit than Conv. evap. with low SC, and
- 0.4–0.8 M€/year (1.2–2.4 €/ADt) higher profit than Conv. evap. with normal SC.

For the conventional plants with 7 and 8 evaporation effects, the additional profit from decreasing the SC temperature (0.2–0.3 M€/year) is independent of the steam value, since the steam demands with high and low SC are equal. In contrast, with 6 effects, there is no additional profit by lowering the SC temperature since the steam demand for the low SC plant was marginally higher than for the normal SC plant.

For the PI plants, the trend is the same for 6 and 7 effects as for the conventional plants. However, for PI_1 with 8 effects, it was possible to use the excess heat in one more effect in the low SC plant than in the normal SC plant, resulting in a lower steam demand. This gives a 0.5–0.6 M€ higher profit for steam values 8–13 €/MWh.

Table 2. Summary of the Resulting Heat Transfer Areas, Investment Costs and Steam Demands for the Three Groups of Simulations

		Total area	Investment	Steam demand	
		[m^2]	[M€]	[MW]	[GJ/ADt]
PI evaporation					
Conv. evap.	6 effects	20 200	38.9	41.0	3.54
	7 effects	26 300	42.1	35.5	3.07
	8 effects	35 100	46.5	31.1	2.69
PI_1 evap.	6 effects	21 600	39.4	32.8	2.83
	7 effects	29 800	43.7	26.4	2.28
	8 effects	43 300	49.7	23.2	2.00
PI_2 evap.	6 effects	23 900	40.5	24.5	2.11
	7 effects	38 000	46.5	17.5	1.51
	8 effects	65 700	56.2	14.9	1.29
Lower surface condenser					
Conv: Low SC	6 effects	16 500	37.8	41.5	3.59
	7 effects	20 500	40.0	35.4	3.06
	8 effects	26 000	43.5	31.0	2.68
PI_1: Low SC	6 effects	17 100	38.0	32.9	2.84
	7 effects	22 500	41.5	26.4	2.28
	8 effects	30 400	45.4	21.6	1.87
Lignin extraction					
Conv: 125%	6 effects	25 300	44.5	51.2	3.54
	7 effects	32 900	48.2	44.4	3.07
	8 effects	43 800	53.2	38.9	2.69
Conv: with LE	6 effects	26 300	44.9	56.7	3.92
	7 effects	34 800	49.1	49.0	3.39
	8 effects	47 300	54.7	43.1	2.98
PI_1: with LE	6 effects	28 200	45.8	46.4	3.20
	7 effects	37 100	50.0	37.6	2.60
	8 effects	52 900	57.1	32.9	2.28

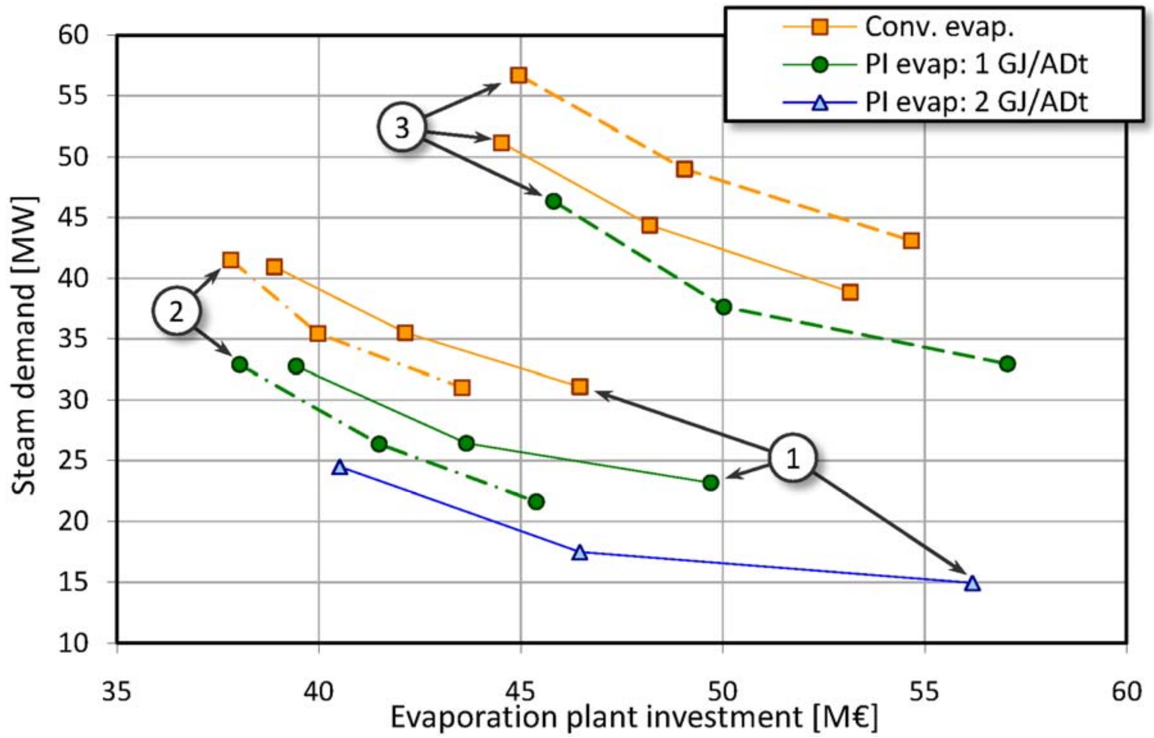

Fig. 2. The steam demands and investment costs resulting from the simulations. Eight evaporation cases are simulated with 6–8 evaporation effects; each one is represented by a line. The solid lines represent the cases for Group 1 (PI evaporation) and a conventional (Conv.) case with increased production to aid comparisons within Group 3 (Lignin extraction). The dash-dotted lines represent Group 2 (Low SC), while the dashes represent the plants in Group 3 with lignin extraction. The Conv. plants are marked by orange squares, the PI_1 plants by green circles and the PI_2 plants by blue triangles.

Group 3: Lignin extraction

The economic consequences of extracting lignin in conventional plants and PI_1 plants are shown in Fig. 6. For steam values between 8 and 13 €/MWh, the economically preferable PI_1 plant is 0.3–0.7 M€/year (0.7–1.7 €/ADt) more profitable than the best Conv. plant with lignin extraction. For the PI_1 plants, 7 effects is the best alternative, whereas either 7 or 8 effects may be the best choice for the conventional plants. With high future electricity prices, 8 effects is the best alternative for the conventional plants.

With lignin extraction, the limit where 7 effects are preferable over 6 effects is 7 €/MWh for conventional plants and 6 €/MWh for PI_1 plants; the same limits for 8 effects are 12 and 20 €/MWh, respectively.

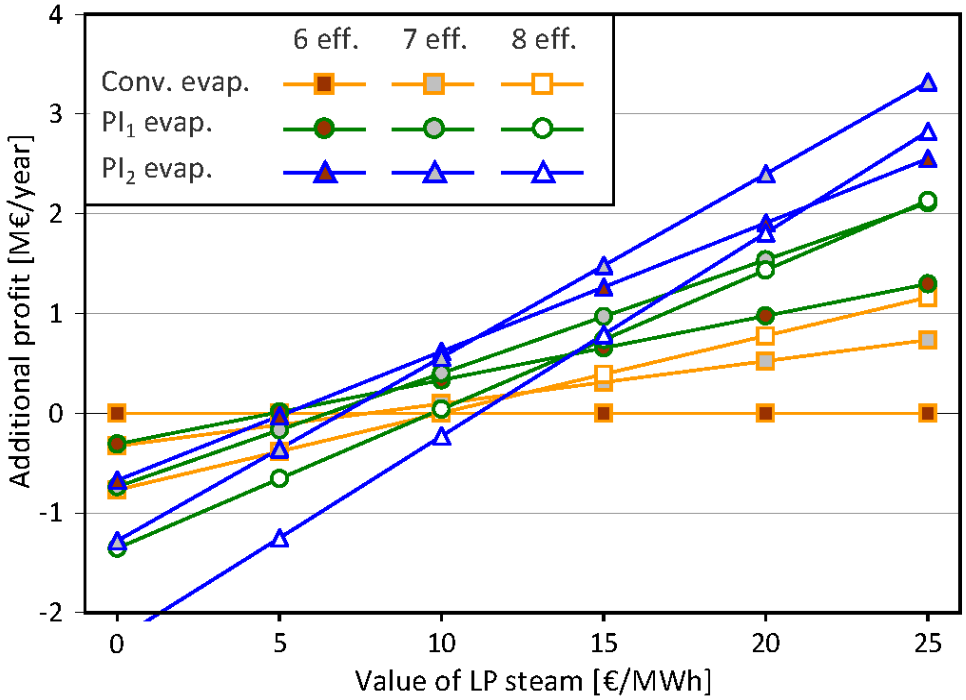

Fig. 3. Group 1, PI evaporation. The additional profit from 6–8 evaporation effects (eff.) for conventional (Conv.), PI_1 and PI_2 plants. The reference plant is the 6-effect Conv. plant.

Sensitivity to the Temperature of the Excess Heat

The temperature of the excess heat determines where the heat can enter the evaporation plant. The higher the temperature of the excess heat is, the more effects can make use of the heat, since the steam temperature decreases stepwise along the evaporation train. In the simulated plants, the excess heat (105°C) generally enters Effect 3.

In supplementary simulations, the consequences of excess heat entering Effect 2 or 4 are investigated. For these examples, the temperature has to be above 121°C or 94°C, respectively, for PI_1 with 7 effects. With excess heat at 121°C, the steam demand decreases by 2 MW (7%), whereas at 94°C it increases by 2 MW (7%). The investment costs necessary are roughly the same as for 105°C. With the higher or lower excess heat temperature, the yearly profit would be 0.1–0.2 M€ higher or lower for the PI_1 plant with 7 effects.

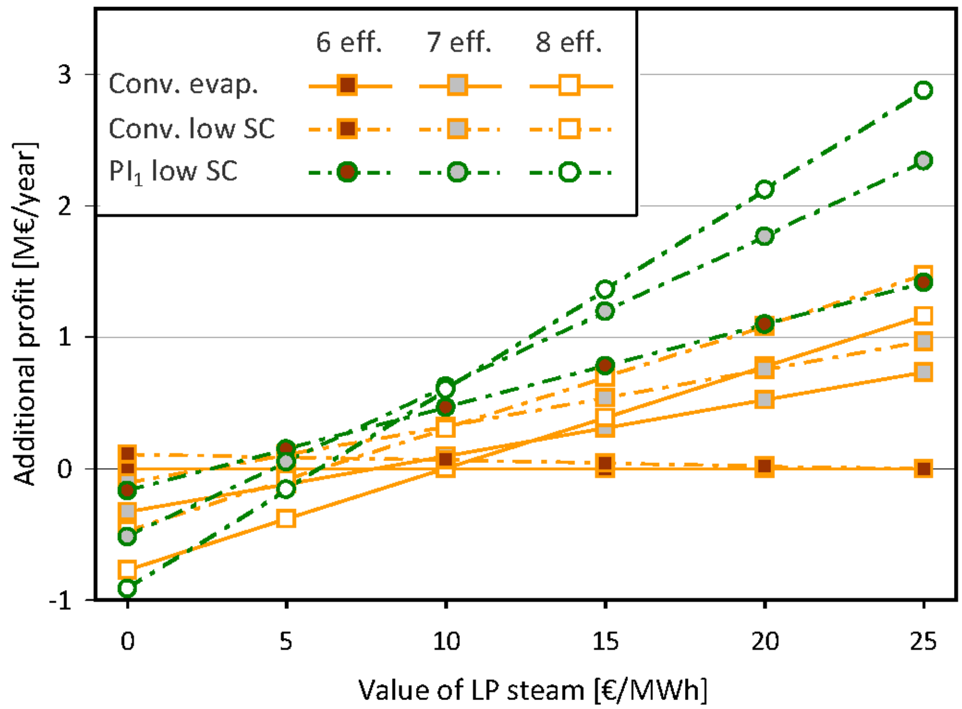

Fig. 4. Group 2, Low SC. The additional profit from 6–8 evaporation effects (eff.) for Conv. and PI_1 plants with low SC, and Conv. plants with normal SC. The reference plant is the 6-effect Conv. plant with normal SC.

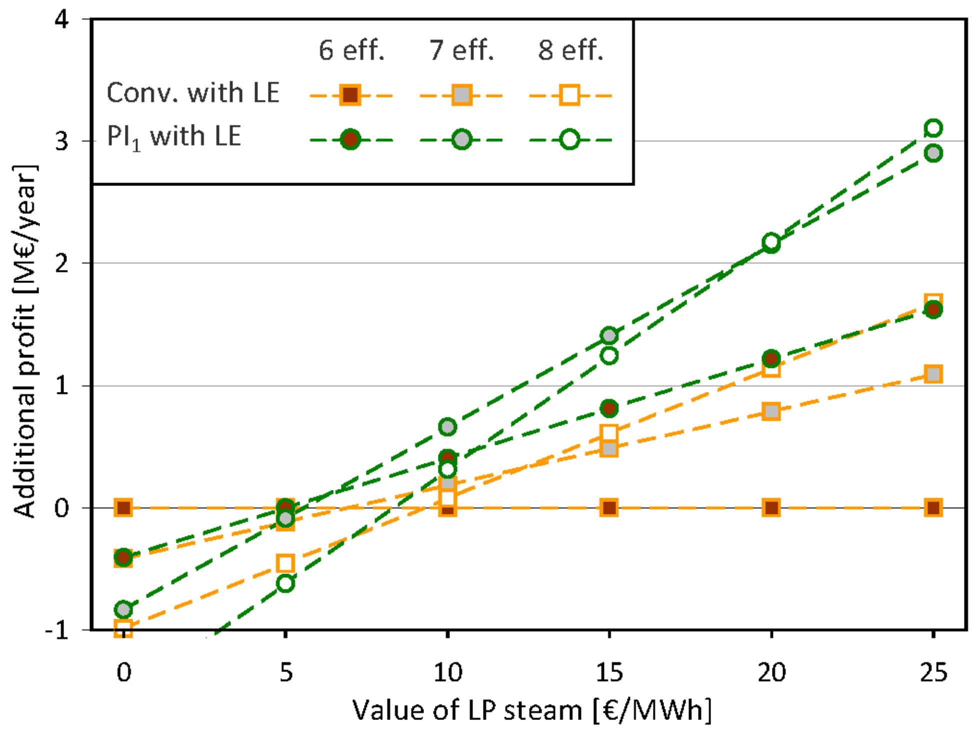

Fig. 5. Group 2, Low SC. The additional profit from 6–8 evaporation effects (eff.) for PI_1 with low SC and PI_1 with normal SC. The reference plant is the 6-effect Conv. plant with normal SC.

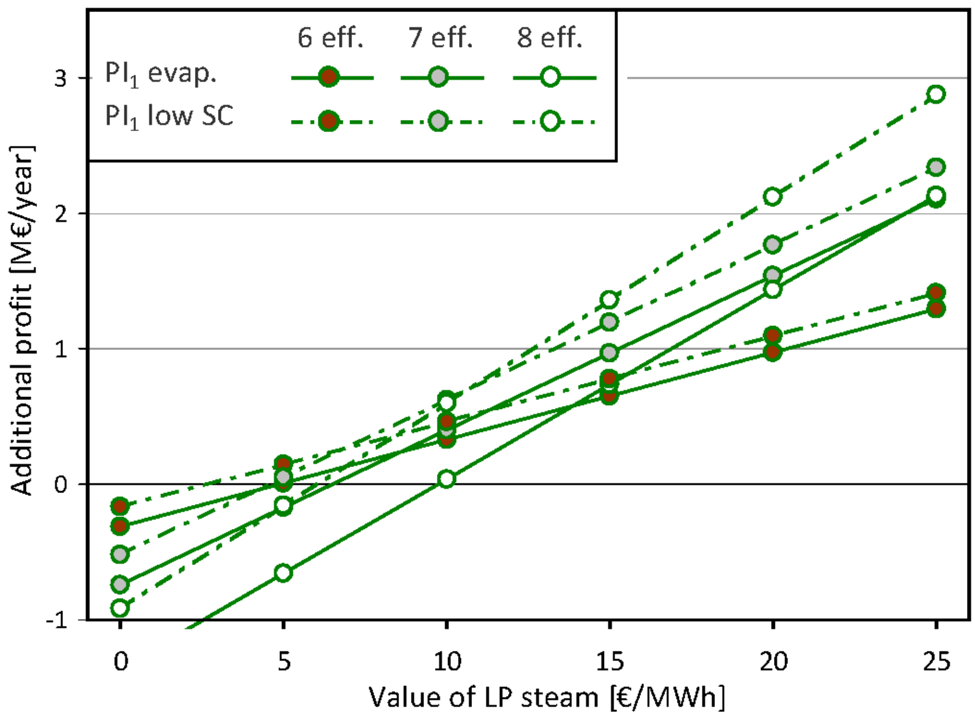

Fig. 6. Group 3, Lignin extraction. The additional profit from 6–8 evaporation effects (eff.) for Conv. and PI_1 plants with lignin extraction (LE). The reference plant is the 6-effect Conv. plant with LE.

CONCLUSIONS

1. By using a PI evaporation plant instead of a conventional plant, a lower steam demand can be achieved even when employing one less evaporation effect. For steam values between 8 and 13 €/MWh, the additional profit of the PI_1 plants is 0.1–0.5 M€/year (0.3–1.5 €/ADt) in comparison with the conventional plants. With predictably higher energy prices in the future, the additional profit with PI plants could increase further. The temperature of the excess heat and the value of the steam saved are important: At low steam values, the gain of using excess heat in the 7-effect PI_1 plant is negligible or negative if the heat is forced to be used in one less evaporation effect.
2. By lowering the temperature of the surface condenser, the profit is raised by 0.2–0.3 M€/year (0.6–0.9 €/ADt) for both conventional and PI_1 plants. This means that the extra costs for the higher volume flows are low compared with the savings from a greater ΔT_{tot}.
3. With an integrated lignin separation plant, the gains are especially high with a PI_1 plant: The best PI_1 plant is 0.3–0.7 M€/year (0.7–1.7 €/ADt) more profitable than the best conventional plant.

ACKNOWLEDGEMENTS

The work presented here is a part of a Swedish national research programme called ‘‘Future Resource-Adapted Pulp Mill, Part 2’’ (FRAM 2). Funding for the present project was provided by the Swedish Energy Agency. We thank Mattias Redeborn and Lennart Delin (ÅF-Process), Lars Olausson (Metso Power), Anders Asblad (CIT Industriell Energianalys), and Ali Moosavifar (Chalmers University of Technology) for valuable discussions. We also thank Lora Sharp McQueen for editing.

REFERENCES CITED

Algehed, J. (2002). “Energy efficient evaporation in future kraft pulp mills,” Ph.D. thesis, Dept. of Heat and Power Technology, Chalmers University of Technology, Goteborg, Sweden.

Algehed, J., Wising, U., and Berntsson, T. (2002). “Energy efficient evaporation in future pulp and paper mills,” In: 7th Conference on New Available Technologies. SPCI, Stockholm, Sweden.

Axelsson, E. (2008). “Energy export opportunities from kraft pulp and paper mills and resulting reductions in global CO_2 emissions,” Ph.D. thesis, Division of Heat and Power Technology, Chalmers University of Technology, Goteborg, Sweden.

Axelsson, E., Olsson, M. R., and Berntsson, T. (2006a). “Heat integration opportunities in average Scandinavian kraft pulp mills: Pinch analyses of model mills,” *Nord. Pulp Paper Res. J.* 21(4), 466-475.

Axelsson, E., Olsson, M. R., and Berntsson, T. (2006b). “Increased capacity in kraft pulp mills: Lignin separation and reduced steam demand compared with recovery boiler upgrade,” *Nord. Pulp Paper Res. J.* 21(4), 485-492.

Cripps, H. R., Melton, A. W., Capell, R., and Retsina, T. (1996). “Pinch integration achieves minimum energy evaporation capacity,” In: 1996 Engineering Conference, Chicago, ILL, USA, Vol. 1, 399-402.

Delin, L. (2008). Senior consultant, ÅF-Process AB, Stockholm, Sweden. Personal communication.

FRAM (2005). Final Report Model Mills (Future Resource-Adapted Pulp Mill research programme). Tech. Rep., STFI-Packforsk, Stockholm, Sweden.

Hadwaco Ltd. Oy (2000). “From effluent to fresh water by cost-effective surplus heat or electrically driven evaporation,” Tech. Rep., Helsinki, Finland.

Kayser, M., Kokotovich, S., and Retsina, T. (1998). “Pinch analysis reveals potential at International Falls Mill,” In: Proceedings of the TAPPI International Engineering Conference, Vol. 3, 1159–1166.

Kemp, I. (1986). “Analysis of separation systems by process integration,” *J. Separ. Proc. Technol.* (7), 9-23.

Moosavifar, A. (2008). “Lignin extraction from black liquor: properties of the liquors and sulphur content in the lignin,” Ph.D. thesis, Forest Products and Chemical Engineering, Chalmers University of Technology, Goteborg, Sweden.

Moosavifar, A., Sedin, P., and Theliander, H. (2006). “Viscosity and boiling point elevation of black liquor: Consequences when lignin is extracted from the black

liquor," *Nord. Pulp Paper Res. J.* 21(2), 180-188.
Olauson L. (1979). "Heat economy improves with Lockman preevaporation using digester flash steam," *Pulp and Paper Canada* 80(3), 45-48.
Olausson, L. (2008). General Manager, Technology & Engineering, Metso Power. Personal communication.
Olsson, M. R. (2009). "Simulations of energy-efficient evaporation including lignin extraction in kraft pulp mills," Ph.D. thesis, Division of Heat and Power Technology, Chalmers University of Technology, Goteborg, Sweden.
Olsson, M. R., Axelsson, E., and Berntsson, T. (2006). "Exporting lignin or power from heat-integrated kraft pulp mills: A techno-economic comparison using model mills," *Nord. Pulp Paper Res. J.* 21(4), 476-484.
Olsson, M. R., and Berntsson, T. (2007). "A tool for simulating energy-efficient evaporation using excess heat in kraft pulp mills," In: 2007 Engineering, Pulping & Environmental Conference. TAPPI, Jacksonville, FL, USA.
Redeborn, M. (2008). Segment Manager, Chemical Pulping, ÅF-Process AB, Stockholm, Sweden. Personal communication.
Reese, D. (2006). "Energy: Feeling the pinch," *Paper 360°* (Sept), 14-18.
Towers, M. (2005). "Energy reduction at a kraft mill: Examining the effects of process integration, benchmarking, and water reduction," *TAPPI Journal* 4(3), 15-21.
Wennberg, O. (1990). "Sulfat- och sulfitlutars fysikalisk-kemiska egenskaper," Slutrapport etapp II, STU projektnr 88–03869 (in Swedish). Tech. Rep.
Wising, U. (2003). "Process integration in model kraft pulp mills: Technical, economic and environmental implications," Ph.D. thesis, Dept. of Chemical Engineering and Environmental Science, Chalmers University of Technology, Göteborg, Sweden.
Öhman, F. (2008). Senior Research Associate, STFI-Packforsk, Stockholm, Sweden. Personal communication.

Article submitted: May 30, 2009; Peer review completed: July 2, 2009; Revised version received and accepted: Oct. 1, 2009; Published: Oct. 2, 2009.