Evaluation of a Value Prior to Pulping-thermomechanical pulp business concept: Part 2

E.M. BILEK, CARL HOUTMAN, AND PETER INCE

ABSTRACT: Value Prior to Pulping (VPP) is a novel biorefining concept for pulp mills that includes hydrolysis extraction of hemicellulose wood sugars and acetic acid from pulpwood prior to pulping. The concept involves conversion of wood sugars via fermentation to fuel ethanol or other chemicals and the use of remaining solid wood material in the pulping process. This paper provides an overview of the methods and results from analysis of the concept as a hypothetical business investment at a pulp and paper mill equipped for making thermomechanical pulp (TMP).

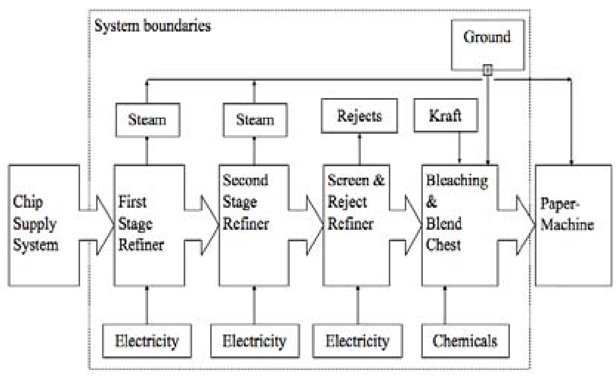
Application: Traditional pulp and paper manufacturing may benefit from process synergies by integrating new biorefining concepts.

We developed an economic model to analyze the VPP–TMP (Value Prior to Pulping– thermomechanical pulp) concept as an incremental business investment at pulp and paper mills equipped for making TMP. The structure of our model integrates process modeling and economic cash flow analysis. Our model includes an engineering analysis of hemicellulose extraction, hydrolysis and fermentation processes, and a financial cash-flow analysis that projects revenues and returns. The model also includes a framework for risk assessment and sensitivity analysis to evaluate the effects of uncertainty or variability in product prices, production costs, or related process parameters. The experimental basis of the operational parameters is described in Part 1 [1]. Our VPP–TMP model is based on Microsoft Excel and is available on-line at State University of New York (SUNY) College of Environmental Science and Forestry (ESF)'s VPP website (http://www.esf.edu/pbe/vpp/).

In Part 2, we also interpret results of four modeled VPP–TMP scenarios, with variation in wood species and intensity of pretreatment. Our model and scenarios incorporate process relationships and pilot data acquired in VPP experiments at the Forest Products Laboratory and collaborating institutions [1]. The data are intended to realistically represent the VPP concept at a medium-sized pulp and paper mill producing lightweight coated (LWC) paper from TMP blended with groundwood pulp and bleached kraft market pulp. However, we emphasize that users must derive technical data to fit their specific business case as appropriate. In addition, users must apply due diligence to determine independently whether the VPP concept will be both technically and financially feasible.

BASE-CASE PROCESS MODEL

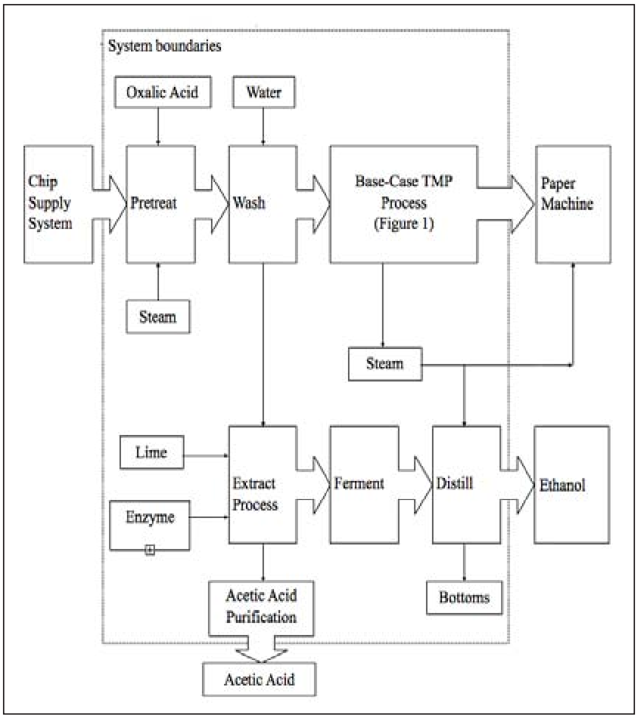
Figure 1 is a block diagram of the base-case TMP pulp and paper process (without VPP), including refining, bleaching, and blending with kraft and groundwood pulps prior to papermaking. This base-case process is represented in our VPP–TMP model. Process parameters can be adjusted to represent alternative mill capacities or designs (i.e., with or without blending kraft or groundwood pulps). Boundaries of analysis begin with wood chips entering the first-stage refiners of the TMP process and end with bleached and blended pulp going to the paper machine. Energy and mass balances are developed on a first-principles basis and can be found in appropriate worksheets of the model.



1. Block diagram of the base-case thermomechanical pulp (TMP) and paper process.

The VPP–TMP process

Figure 2 is a block diagram of the VPP–TMP process concept, which is also included in our VPP–TMP model. Before entering the TMP process, wood chips are subjected to an oxalic acid (OA) pretreatment, producing a solution of oligomers by the preferential extraction of hemicellulose. The solution of oligo-



2. Block diagram of the Value Prior Pulping (VPP)–TMP process concept with hemicellulose extraction and fermentation to ethanol.

mers is subsequently hydrolyzed, neutralized, and fermented to ethanol. Acetic acid is also produced as a byproduct of the extraction process. As shown in Fig. 2, the VPP–TMP process model also incorporates the TMP process shown in Fig. 1; however, with the introduction of VPP, operating parameters of the TMP may require adjustment. For example, VPP chip pretreatment results in reduced energy requirements in TMP refining, with a corresponding increase in TMP throughput. Pulp quality may improve, thereby reducing the quantity of purchased kraft or groundwood supplemental pulps.

VPP–TMP scenarios

We modeled four hypothetical scenarios to assess the feasibility of VPP–TMP in the context of a modeled lightweight coated (LWC) paper mill. Our four VPP–TMP scenarios reflect use of alternative pulpwood species in the TMP process (aspen, spruce, or pine) and also variation in OA pretreatment level for pine. Our four scenarios are labeled as follows: (1) aspen, (2) spruce, (3) pine low OA, and (4) pine high OA.

Table I displays values of key process inputs and outputs per day for the base case (without VPP) and the four alternative VPP–TMP scenarios. TMP refiner electric energy input and LWC paper production were held constant in all scenarios relative to the base case, so as to isolate from our analysis the effects of variation in those parameters and focus instead

	Base Case	Alternative VPP–TMP Scenarios			
		Aspen	Spruce	Pine Low OA	Pine High OA
Input Variables					
Green wood chips to TMP (kg/day)	600,000	844,775	870,976	743,515	915,326
Electric energy input to TMP (MW·h/day)	622	622	622	622	622
(see Table II for TMP refining specific energy requirements)					
Oxalic acid for chip pretreatment (kg/day)	–	3,567	234	1,662	4,092
Hydrogen peroxide for TMP (kg/day)	11,625	9,466	11,625	12,124	18,933
Sodium hydroxide for TMP (kg/day)	7,266	6,705	7,266	7,577	10,255
Sodium bisulfite for TMP (kg/day)	2,906	4,224	2,906	3,031	4,733
Lime for extract processing (kg/day)	–	2,969	195	1,384	3,407
Kraft market pulp input (dry kg/day)	249,115	199,292	249,115	224,203	199,292
Groundwood pulp input (dry kg/day)					
	290,634	248,546	177,294	269,489	230,958
(see Table II for kraft and groundwood pulp percentages of total pulp)					
Output Variables					
LWC paper production (dry kg/day)	976,920	976,920	976,920	976,920	976,920
Ethanol production (kg/day)	–	9,268	5,183	8,249	16,880
Acetic acid production (kg/day)	–	1,049	541	462	568
Net steam recovery from TMP (kg/day)	729,318	531,848	540,319	576,246	468,149
Water to treatment plant (kg/day)	120,000	120,000	120,000	120,000	243,148
Solid wastes @ 50% solids (kg/day)	258,868	364,589	371,618	316,257	385,954

I. Key process inputs and outputs per day for alternative VPP–TMP scenarios.

	Alternative VPP–TMP Scenarios			
Variable Process Assumptions	**Aspen**	**Spruce**	**Pine Low OA**	**Pine High OA**
OA loading (% on wood weight)	0.85	0.069	0.45	0.9
Hydrogen peroxide (% on pulp weight)	1.5	2	2	3
Sodium bisulfite (% on pulp weight)	1*	0.5	0.5	0.75
Hemicellulose removed, total (% total available)	10	3	10	20
Acetic acid removed (% wood treated)	0.5	0.25	0.25	0.25
Primary refining specific energy (MWh/MT) (MWh/t)	0.8288	0.784	0.952	0.784
Secondary refining specific energy (MWh/t)	0.518	0.49	0.595	0.49
Rejects refining specific energy (MWh/MT)	0.518	0.49	0.595	0.49
Kraft market pulp (% fraction total pulp)	24	30	27	24
Groundwood pulp (% fraction total pulp)	30	21	32	28
Fixed Process and Economic Assumptions	(applied to all scenarios)			
Wood moisture content (% total weight)	50			
Extractives removed (% total available)	50			
Cellulose removed (% total available)	0			
Hemicellulose removed in 1st plug-screw (% wood)	2			
Pretreat temperature (°C)	130			
LWC coating weight (% of paper weight)	15			
Conversion monosaccharide to ethanol (%)	46			
Conversion oligos to ethanol (%)	20			
TMP mill process labor (workers/day)	24			
Ethanol plant process labor (workers/day)	12			
Pretreatment capital cost ($/o.d. ton/yr)	215	*Bisulfite for aspen was added during the pretreatment.		

II. Process data and economic assumptions for four alternative VPP–TMP scenarios.

on process economic impacts of the VPP–TMP concept.

Various input and output relationships were projected to change with VPP. For example, as shown in Table I, the kraft and groundwood pulp input quantities may change because the quality and output volume of TMP pulp increased with VPP chip pretreatment, allowing substitution of TMP for kraft or groundwood pulp (assuming constant power input to TMP refiners and lower specific energy requirements because of chip pretreatment). For purposes of this model, we assumed that a combination of throughput increases and widening the plate gap could give the required reduction in specific energy. Wood chip supply to TMP increased in all four VPP–TMP scenarios as more wood input was needed with higher TMP output and biorefinery coproducts (ethanol and acetic acid). Net steam recovery, based on the energy and mass balance from TMP refining, was reduced with VPP pretreatment, and chemical inputs to TMP also changed with increased refining energy efficiency and TMP throughput.

Table II displays more specific process data and economic assumptions for the four VPP–TMP scenarios. On the basis of our pilot laboratory results [1], the scenarios featured different wood species used in TMP and different levels of OA pretreatment, which contributed to different levels of specific energy required in the TMP refiners (primary, secondary, and rejects refining). However, with fixed power input to refiners in all scenarios (Table I), the result of changes in specific refining energy was to change the TMP pulp quality and output volume, and thus change the required fractions of kraft market pulp and groundwood pulp (Table II). Variation in wood species, OA treatment levels, and pulp quality also resulted in different TMP chemical input requirements (hydrogen peroxide and sodium bisulfite) and different levels of hemicellulose and acetic acid removal from wood chips. Apart from those differences, the scenarios all shared a common set of general assumptions about other parameters such as wood moisture content, extractives and cellulose removal efficiency in chip pretreatment, fermentation efficiencies, labor inputs, and pretreatment capital costs per ton of throughput (Table II).

FINANCIAL FEASIBILITY MODEL

Our VPP–TMP model produced a financial analysis based on differences in projected cash flows between VPP–TMP scenarios and the base case (without VPP). The differences or incremental cash flows were used to compute financial performance measures for the VPP investment, including discounted net present value (NPV) and internal rate of return (IRR), which are used to evaluate feasibility of the business concept. Cash flow worksheets in our model were based on a published cash flow model written in Microsoft Excel, called ChargeOut! [2].

Our VPP–TMP model computed financial performance measures in three ways: before tax and finance, before tax, and after tax (the latter two options include the effects of capital financing or borrowing). The model offered much flexibility in representing alternative financing arrangements and development grant options. (SUNY-ESF's VPP website also provides a business planning guide for VPP concepts, including information about financing and business structures, due diligence, and other relevant considerations.)

Basic economic assumptions

Our economic assumptions (**Table III**) were based on recent historical U.S. market values for the various inputs and outputs. We assumed that costs, as well as TMP mill unit revenue prices and process steam unit revenues, would increase at an inflation rate of 3.0% per year, and ethanol unit revenues would increase at 5.0%, but it is also possible to apply projections of future market values. For example, our assumed average wholesale market value for the fuel ethanol product was \$0.64 per kg (equivalent to \$1.91 per U.S. gallon), based on the prevailing trend in midwestern U.S. wholesale fuel ethanol prices in 2009 to early 2010. However, wholesale ethanol market prices have varied historically, with real prices ranging in recent years from around \$1.90 per gallon in early 2010 to an average of around \$2.50 per gallon in 2008 [3]. Although U.S. average ethanol prices declined from 2008 to early 2010, prices began to rebound in the second half of 2010, and annual average real prices for wholesale fuel ethanol were projected to range from around \$1.85 per gallon to just over \$2.15 per gallon over the next 20 years, according to the 2010 Annual Energy Outlook [3]. Thus, it was appropriate to apply sensitivity analysis and risk assessment to results.

Variable Inputs	Price or Value
Wood chips (\$/t)	64.00
Electricity (\$/MWh/MT)	65.30
Oxalic acid (\$/kg)	1.00
Lime (\$/kg)	0.11
Hydrogen peroxide (\$/kg)	1.19
Sodium hydroxide (\$/kg)	0.30
Sodium bisulfite (\$/kg)	0.60
Kraft pulp (\$/t)	742.50
Groundwood pulp (\$/t)	423.00
Water treatment (\$/t)	1.00
Solid waste disposal (\$/t)	40.00
TMP mill process labor (\$/worker/day)	208.00
Ethanol plant process labor (\$/worker/day)	208.00
Other TMP mill variable operating costs (\$/t)	250.00
Other ethanol plant variable operating costs (\$/kg)	0.10
Variable Outputs	**Price or Value**
Lightweight coated paper product (\$/t)	915.00
Fuel ethanol product (\$/kg)	0.64
Acetic acid (\$/kg)	0.40
Process steam (\$/t)	24.00

III. Input and output price or value assumptions applied to VPP–TMP scenarios.

Summary financial measures

Summary financial measures may be used to decide whether an investment promises to be a worthwhile undertaking with regard to financial returns. Net present value (NPV) and internal rate of return (IRR) are two common financial measures. NPV represents a project's contribution to wealth and IRR is an interest rate at which NPV = \$0 [4]. The more positive a project's NPV and the higher its IRR, the more attractive an undertaking it might be.

Our VPP–TMP model computed the financial performance of the VPP investment several different ways: before tax and finance, before tax, and after tax. IRR was calculated both in nominal terms (including inflation) and in real terms (without inflation). The calculations were done using Excel's inbuilt NPV and IRR formulas, which are based on standard managerial accounting formulas, such as the following formulas for NPP and IRR in Eqs. (1) and (2):

$$NPV = \sum_{t=0}^{n} \frac{(B_t - C_t)}{(1+ARR)^t} \quad (1)$$

Where:

B_t = benefits (revenues) received in year t

C_t = costs incurred in year t

ARR = alternative rate of return, or the discount rate expressed in decimal form

n = the economic life of the equipment (number of years for the analysis; the model is set up to run where n is any whole number from 2 to 20; in our sample configuration, $n = 20$)

And, if

$$\$0 = \sum_{t=0}^{n} \frac{(B_t - C_t)}{(1+d)^t} \quad (2)$$

then d = IRR, where all variables are as previously defined and the IRR (d) is in decimal form.

Scenario	Financial Analysis Results				
	After-Tax Net Present Value (millions $)	Nominal After-Tax Internal Rate of Return (%)	Break-Even Capital for VPP (millions $)	Estimated Capital Required (millions $)	Percentage of Required Return on Capital (nom. ROIC)
Aspen	53.2	36.8	92.3	29.6	11.0
Spruce	36.6	30.2	71.4	28.3	11.0
Pine low OA	11.5	18.2	40.6	27.0	11.0
Pine high OA	38.7	28.1	80.1	34.5	11.0

IV. Expected financial results of four alternative VPP–TMP scenarios.

The alternative rates of return used in the NPV calculations were the minimum required returns on investment capital (ROIC). ROIC included the expected bank deposit interest rate (set at 1% in this analysis), required risk premium (set at 10% in this analysis), and any financing costs and adjustments for tax deductibility of loan interest payments. The computation of ROIC followed the standard weighted average cost of capital formula [4]. The after-tax formula for ROIC incorporated the fact that debt funding is tax deductible in the United States, whereas equity funding is not. In this analysis, we did not include debt financing in any of the scenarios to assess financial performance based purely on returns to total equity, so the ROIC was 11% in all cases (sum of deposit interest rate plus risk premium).

RESULTS

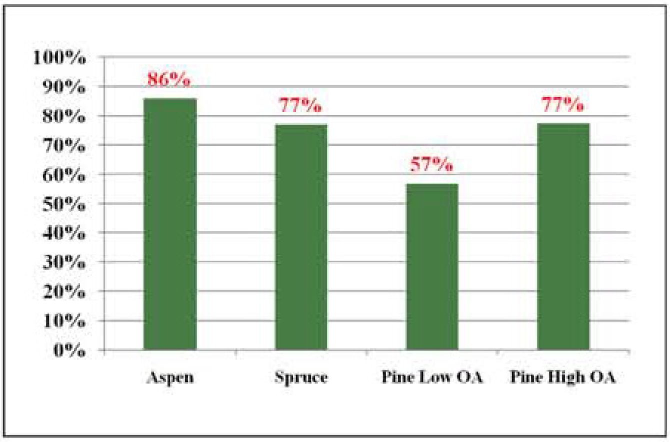
Table IV summarizes expected financial results of the four VPP–TMP scenarios, computed as after-tax results for the incremental VPP investment. After-tax NPV were positive across all four scenarios, ranging from around $12 million to $53 million. NPV represented the expected surplus or margin of economic value generated by the investment over 20 years, which could be extracted up front and still achieve the required return on invested capital (ROIC) of 11%. The expected nominal after-tax IRRs were also positive and substantially higher than the ROIC in all four scenarios, meaning that rates of return in all four scenarios were expected to be considerably higher than the sum of the deposit interest rate plus the required risk premium. Estimated capital requirements ranged from $27 million to $34.5 million, but all scenarios supported higher break-even values; capital costs could be as high as the break-even values and still yield the nominal ROIC.

For purposes of this study, we assumed that the electrical power infrastructure would be best used if the total electrical load was held constant. Benefits of pretreatment with oxalic acid may be taken two ways. The chips could be processed with higher throughput, thereby saving specific energy. This was the result shown by Kang et al. [5]. Alternatively, the chips may be processed at the same throughput and specific energy, thereby increasing the resulting TMP pulp quality and reducing the amount of necessary market pulp to achieve the same LWC pulp quality. On the basis of our pilot trials, we chose to model a combination of these two options, although our model could be reconfigured to illustrate energy savings directly.

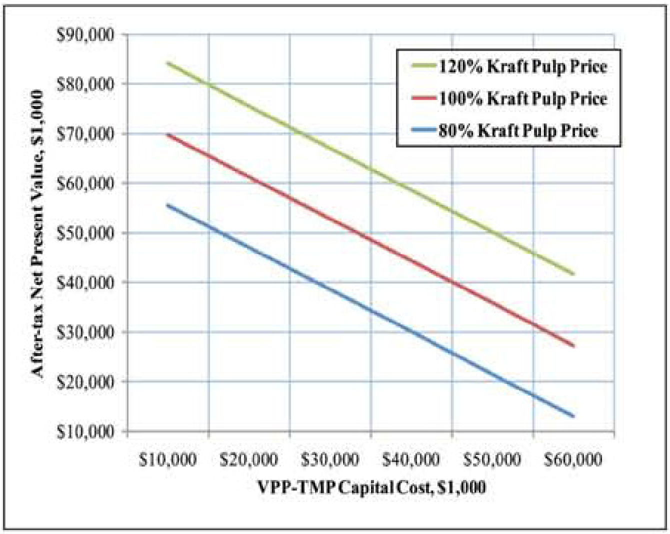
When the benefits portion of the after-tax net present values were broken down into their component parts, the savings that could be attributed to reductions in market pulp accounted for roughly 80%–90% of the total benefits, depending on the scenario (data not shown). In reality, savings would probably be realized through a combination of reduced market pulp and energy savings. Ethanol production contributed roughly 10%–20% of the total benefits.

Although expected NPVs were all positive, there were risks that NPV could be negative (and IRR less than required ROIC) because of variability or uncertainty about model parameters or data values. Therefore, we applied stochastic risk assessment techniques to assess the combined risk associated with uncertainty and variability across the full spectrum of model variables. In particular, we equipped the VPP–TMP model with Monte Carlo simulation capabilities, and we assigned specific variability assumptions to all process and economic variables. Variability assumptions were specified in the model as expected standard deviations of model variables, which can also be expressed as coefficients of variation (ratios of standard deviation to mean values). In this study, specified coefficients of variation included ±13% for ethanol plant capital costs, ±23% for pretreatment facilities capital costs, ±7% for price of wood chips, ±17% for price of kraft market pulp, ±6% for price of OA, ±10% for wood chip moisture content, ±20% for acetic acid removal, ±5% for sugar conversion to ethanol, ±8 for labor inputs, ±12%–19% for refiner specific energy, and ±29% for price of ethanol. Thus, we applied the VPP–TMP model and Monte Carlo techniques to simulate sample distributions of expected financial results, including after-tax NPV, taking into account expected ranges of variability in all product and coproduct prices; production efficiencies; and costs of all raw material inputs, labor, and energy.

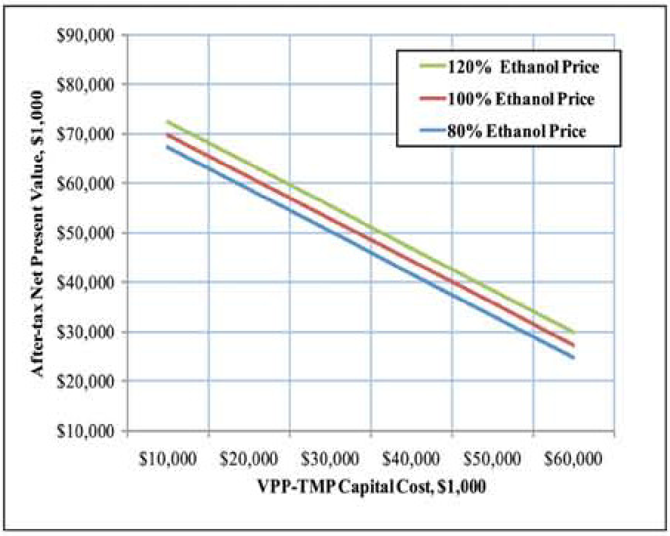
Figure 3 illustrates an example of Monte Carlo simulation results for each of the four VPP–TMP scenarios. Results show the sample likelihood that after-tax NPV would be positive, or that the IRR would exceed the required return on capital or ROIC. (Monte Carlo simulations with 2,000 trials were run



3. Sample likelihood that after-tax net present value (NPV) will be positive (or internal rate of return [IRR] will exceed return on investment capital [ROIC]) for four VPP–TMP scenarios, based on Monte Carlo simulation. [Figure 3 corrected June 2011]



4. Effect of kraft pulp price on after-tax NPV over a range of capital costs.



5. Effect of ethanol price on after-tax NPV over a range of capital costs.

for each scenario, using specified coefficients of variation for model variables.) The results indicate that the VPP-TMP scenarios not only exhibited substantial differences in expected financial outcomes (Table IV) but also differences in their expected likelihood of achieving desirable financial outcomes (Fig. 3). In all scenarios there was a better than 50% likelihood that the incremental VPP-TMP investment would yield an IRR higher than the ROIC. However, in the pine low-OA instance, the likelihood of just 57% meant there was a 43% likelihood of failing to achieve the required ROR. As a general conclusion, the VPP-TMP concept offers a fairly high likelihood of financial success, but would be riskier at lower pretreatment levels.

A closer look at individual variables via sensitivity analysis revealed other noteworthy relationships. For example, we observed that some scenarios had a strong relationship between financial performance and price of kraft market pulp. Economic benefit of reduction in purchased market pulp increased with price of kraft pulp. **Figure 4** shows, for example in the Aspen scenario, the highly positive relationship of expected after-tax NPV to change in kraft pulp price across a range of capital costs.

As would be expected, financial performance of the incremental VPP-TMP investment was also positively correlated with the market price of fuel ethanol. We observed, however, that the sensitivity of financial performance to ethanol price may be much less than the sensitivity to kraft pulp price, as shown in **Fig. 5** for the aspen scenario. The relatively narrow spacing between the lines in Fig. 5 shows less sensitivity of NPV to ±20% change in ethanol price than the sensitivity of NPV to kraft pulp price shown in Fig. 4. The greater sensitivity of NPV to kraft pulp price is explained by the more significant revenue impacts of reduced kraft pulp input—a reduction of nearly 50 metric tons/day of kraft pulp in the aspen scenario (Table I) at a price of $742.50 per ton (Table III), or a cost savings of about $37,000 per day—while the relatively modest volume of ethanol output increases revenues by only about $5,900 per day (at 9,268 kg or about 3,100 gal/day in the aspen scenario). Thus, in the aspen scenario, revenue gains from reduced kraft pulp input exceeded revenue gains from ethanol output by a ratio of more than 6:1.

The degree of sensitivity to kraft pulp price, ethanol price, or other variables differed substantially among the four VPP-TMP scenarios. There was particular sensitivity to kraft pulp price because the extent to which VPP pretreatment can increase TMP output and improve TMP quality (and reduce purchased kraft pulp) varied by scenario. The base case (without VPP) was assumed to require 30% purchased kraft pulp in the pulp blend, while among the VPP-TMP scenarios, the kraft pulp fractions were projected to be 24% in the aspen scenario, 30% in the spruce scenario, 27% in the pine low OA scenario, and 24% in the pine high OA scenario.

Whereas the economic analysis we have presented appeared to be low risk, many engineering issues would need to be addressed in the design phase that could hinder implementation. Oxalic acid has a long history in other industries, such as leather tanning, metal refining, and dyeing, and the engineering design would require careful choice of construction materials in OA mixing zones. Water chemistry and wood metal ion profile will also require careful consideration. Calcium oxalate scale is a significant problem for bleach towers, and because the proposed levels of OA are relatively low, controlling calcium would be important. Finally, we generated pilot-scale quantities of pulp but did not conduct paper machine trials. Operational issues, such as machine breaks, pitch control, and drainage, remain as unknown risks to implementation of this process.

SUMMARY AND CONCLUSIONS

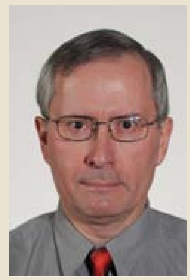
We modeled and analyzed the VPP–TMP business concept as a hypothetical investment at an existing pulp and paper mill, using fairly realistic engineering data and cost estimates for a mill producing LWC paper from TMP that is produced on site and blended with groundwood pulp and bleached kraft market pulp. Our results suggest that the VPP–TMP concept offers a fairly high likelihood of financial success, but would be riskier at lower pretreatment levels (as in our pine low OA scenario). In some scenarios, the largest share of expected economic benefit consisted of pulping process synergies, such as displacement of purchased kraft market pulp, with gains in TMP throughput and quality resulting from reductions in specific energy requirements because of the wood chip pretreatment. For example, in the aspen scenario, the revenue benefits of cost savings that resulted from reduced kraft pulp input exceeded the revenue gains from fuel ethanol by about 6 :1.

These findings corroborate a view that process synergies associated with integrated forest product biorefining concepts (such as process energy savings and increased throughput) may be just as significant economically as the biofuel or chemical coproducts of biorefining. The general observation is that traditional pulp and paper manufacturing may benefit from the process synergies we have observed by integrating new biorefining concepts. In a separate study, to be reported

ABOUT THE AUTHORS


Bilek


Houtman


Ince

There is widespread interest in the concept of converting hemicellulose from wood into ethanol and other biobased products in current wood conversion facilities. In the paper industry, the idea is to extract value from wood chips prior to pulping them (VPP). We felt that a validated and generic economic/business case model of the VPP concept was needed to better assess its economic potential, as well as to help guide ongoing research and development efforts aimed at cost reduction or efficiency improvement. We hoped that such a model would enable mill managers to more easily and cost-effectively evaluate the concept at a prefeasibility level. Also, such a model could perhaps aid the United States in achieving its year 2022 goal, which was set in the Energy Independence and Security Act of 2007, of having 21 billion gallons of ethanol derived from biobased materials other than corn starch.

This work complemented research that Peter Ince and Ted Bilek had done in economic modeling of wood-based production facilities. Also, Ted had recently finished a discounted cash flow model that he thought could be adapted and integrated with an engineering process model. Carl Houtman was doing engineering process modeling and research on oxalic acid extracts of hemicellulose from wood chips. Because research was being done elsewhere on the VPP kraft process, we chose to retool our work and focus on evaluating the VPP process in relation to TMP.

The retooling enabled us to discover some surprising benefits of using VPP with the TMP process. The extra pretreatment of the chips reduced the amount of time (and energy) needed to achieve a given quality pulp. Alternatively, if the chips were processed for the same amount of time, pretreatment resulted in higher-quality pulp, which in turn meant that less kraft pulp had to be added to the resulting blend to achieve a given paper quality. This savings in either energy or market pulp might be an even larger benefit than the value of the ethanol and biochemicals that could be produced.

TMP mill managers can download our model and customize it for their mills' specifications to see whether the VPP concept is worth pursuing. As the next step, we would like to work with mills to further customize and validate the model and to promote the concept in the TMP industry. The potential to both reduce manufacturing costs and produce biofuels is a win-win situation for the industry and the country.

Bilek is an economist, Houtman is a research chemical engineer, and Ince is a research forester at the USDA Forest Service, Forest Products Laboratory, Madison, WI, USA. Email Bilek at tbilek@fs.fed.us.

soon, we analyzed the VPP concept and related process synergies in the context of kraft pulping and papermaking. **TJ**

ACKNOWLEDGEMENTS

The authors gratefully acknowledge grant support from the Forest Service Biomass Marketing and Utilization Program, as well as financial support of the VPP Consortium through the Department of Energy.

LITERATURE CITED

1. Houtman, C.J. and Horn, E., *TAPPI J.* 10(5): 21(2011).
2. Bilek, E.M., "ChargeOut! Determining machine and capital equipment charge-out rates using discounted cash-flow analysis." General Technical Report GTR-171, 2006, Forest Products Laboratory, Madison, WI, U.S. Department of Agriculture, Forest Service. Available [Online] http://www.fpl.fs.fed.us/documnts/fplgtr/fpl_gtr171.pdf
3. USDOE, "Annual energy outlook 2010." Report DOE/EIA-0383(2010), U.S. Department of Energy, 2010, Energy Information Administration, Washington, DC. Available [Online] http://www.eia.doe.gov/oiaf/aeo/pdf/0383(2010).pdf
4. Brealey, R.A. and Myers, S.C., *Principles of Corporate Finance*, 4th edn., McGraw-Hill, New York, 1991, p. 465.
5. Kang, T., Soong, G., Chang, X.F., et al., *Pulp Pap. Can.* 111(6): T82(2010).