Optimization of Sustainable Forest-based Biomass Supply Chains



Taraneh Sowlati, Ph.D., P.Eng.
Professor

Outline

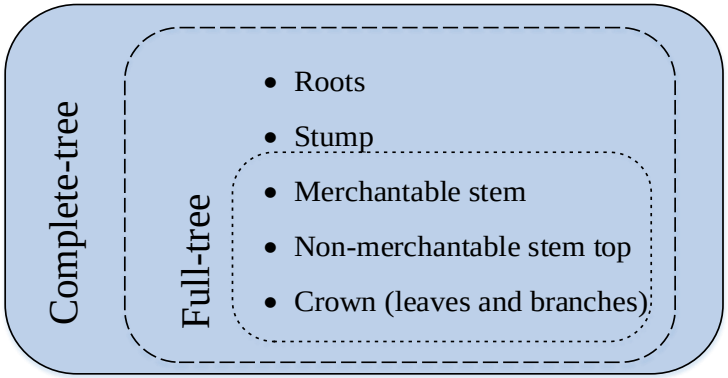
- Background
  - Forest-based biomass
  - Supply chain planning
- Supply chain optimization
  - Model
  - Results
- Conclusions

Background

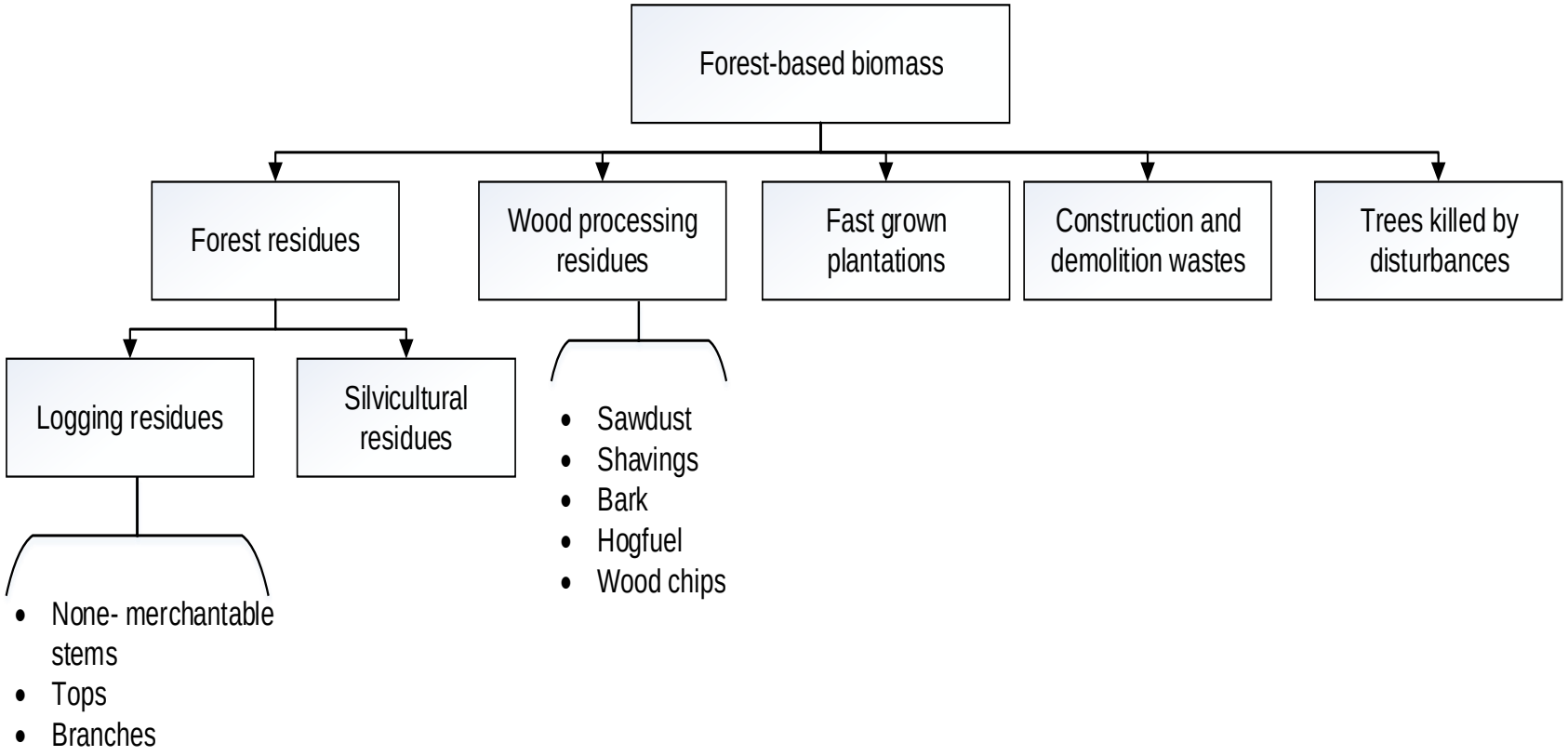
- Forests cover about 1/3 of the earth's surface (FAO 2010)
  - Provide wide range of benefits
  - Represent potential source of renewable material
- Forest biomass refers to the total mass of the wood



Forest biomass



Forest-based biomass

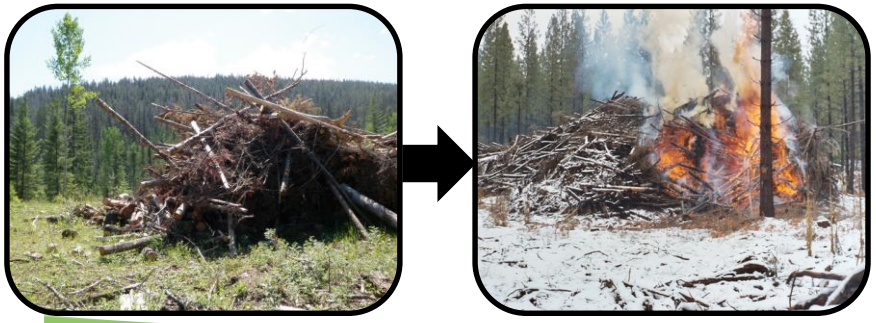


- Can be used in a wide range of application to produce bioenergy and biofuels

Benefits of using forest-based biomass

- Improve the air quality by reducing the emissions from burning them at the roadside or at the mills
- Decrease waste
- Save landfill spaces
- Diminish fire risks by collecting residues after the thinning operations
- Provide a new stream of revenue for forest companies
- Create job opportunities in forest dependent communities
- Generate renewable energy to reduce dependency on fossil fuels

Harvesting residues



Sawmill residues



Photos: Claudia Cambero & ucanr.edu

Challenges of using forest-based biomass

- Bulky material with low heating value and high moisture content
- Large amount has to be delivered to a conversion plant on a regular basis – sourcing a very important activity
- Variability in supply amount and quality
- High transportation and logistics costs – 20-40% of total delivery cost
- Competition for fiber from other potential users

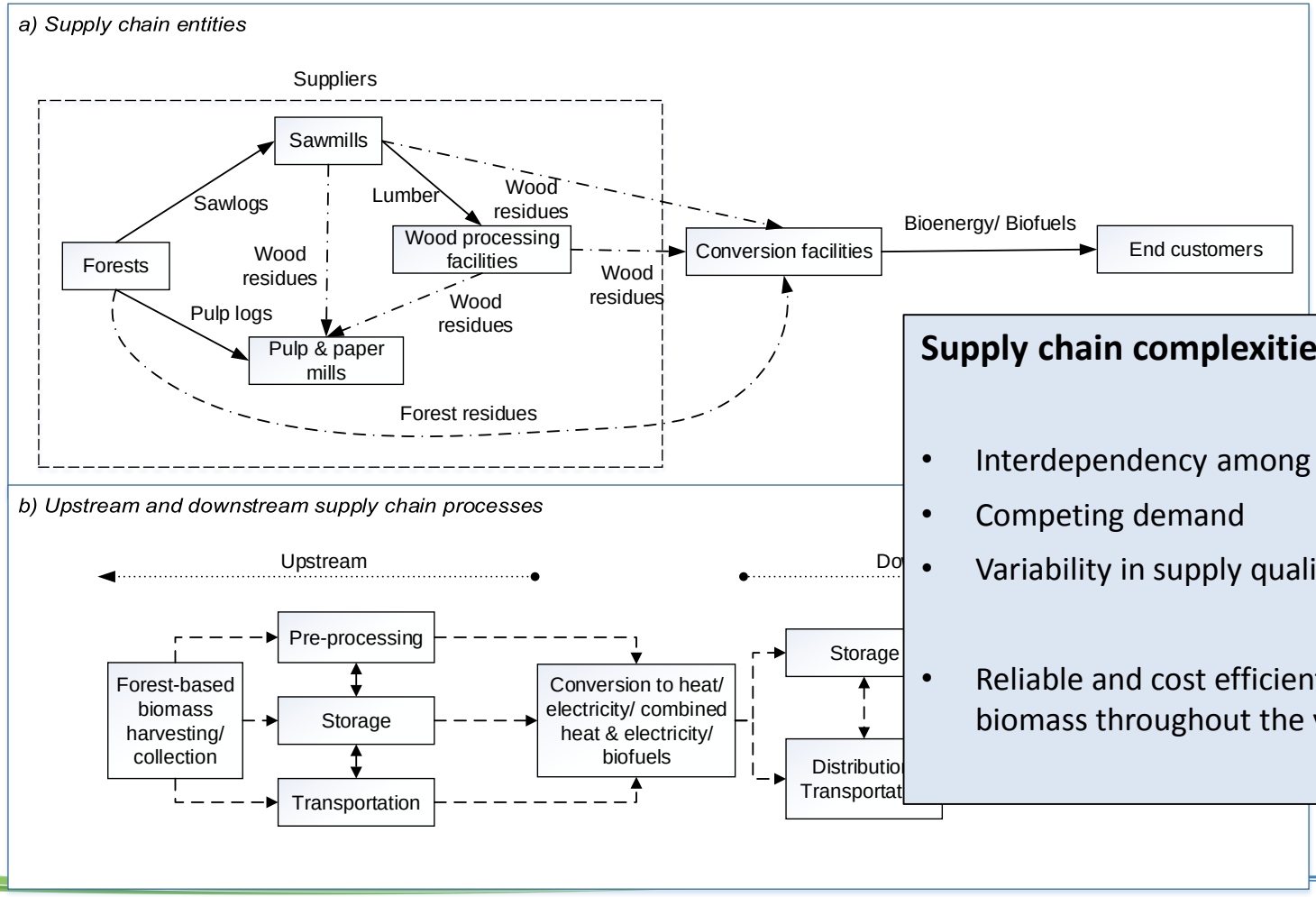


wellonsfei.ca/en/is-biomass-green.aspx



biv.com

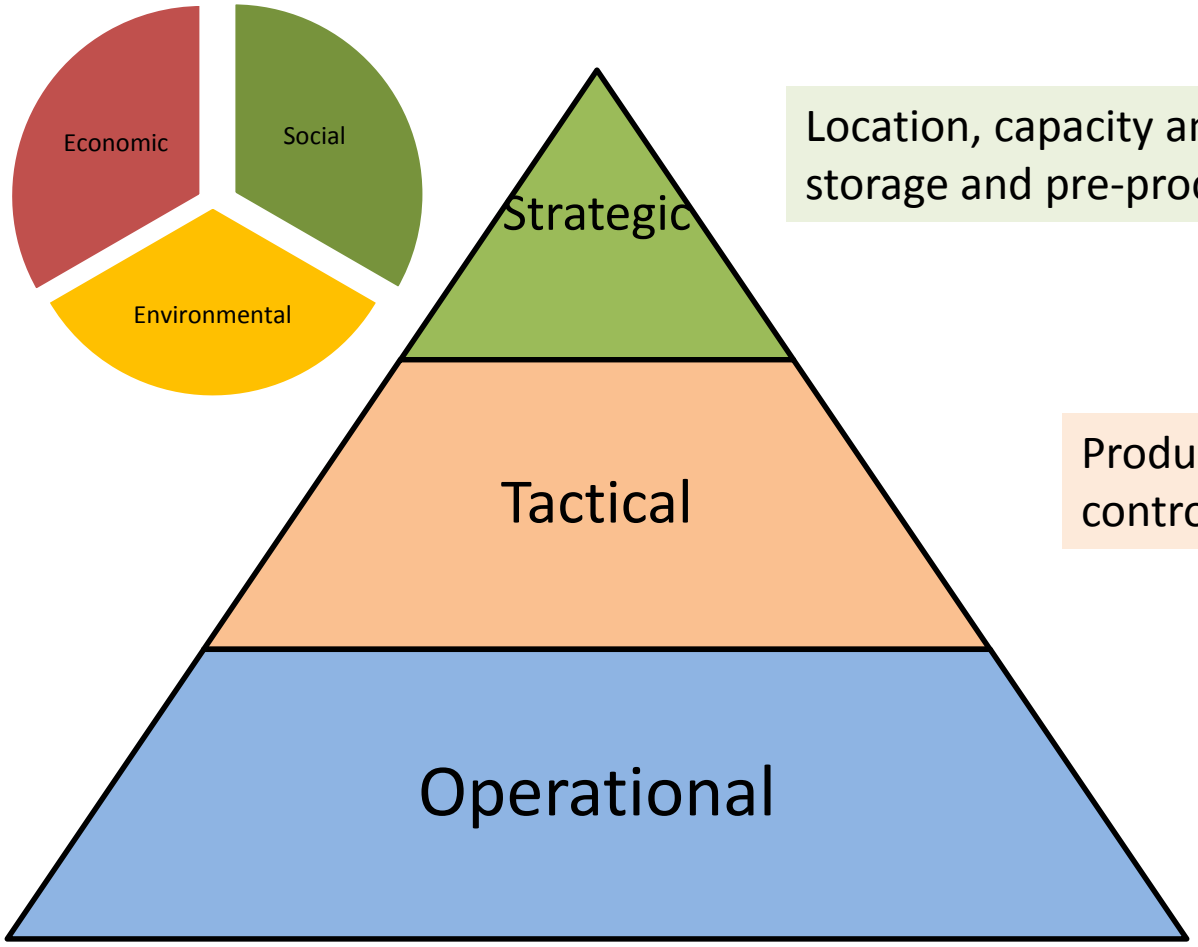
Forest and wood residues supply chain



Supply chain complexities

- Interdependency among forest sectors
- Competing demand
- Variability in supply quality and quantity
- Reliable and cost efficient supply of biomass throughout the year

Supply chain decisions



Location, capacity and number of conversion, storage and pre-processing facilities

Production planning, inventory control, logistics management

Vehicle scheduling and routing

Single objective models

Application	Examples	Remarks
Bioenergy	Frombo et al. (2009a,b), Freppaz et al. (2004), Schmidt et al. (2010).	• Focused on heat and/or power.
Biofuels	Ekşioğlu et al. (2009), Kim et al. (2011), Leduc et al. (2008), Natarajan et al. (2014), Parker et al. (2010), You et al. (2012).	• Mainly focused on bioethanol from agricultural biomass.
Bioenergy & biofuels	Tittmann et al. (2010), Feng et al. (2010).	• No interaction among technologies

- Most models focused on either bioenergy or biofuel production separately.
- Multi-product models assumed no interaction among co-located plants.
- Strategic decisions based on average annual values (no supply and demand variation from year to year).
- The objective function was was to minimize cost or maximize profit of the supply chain.

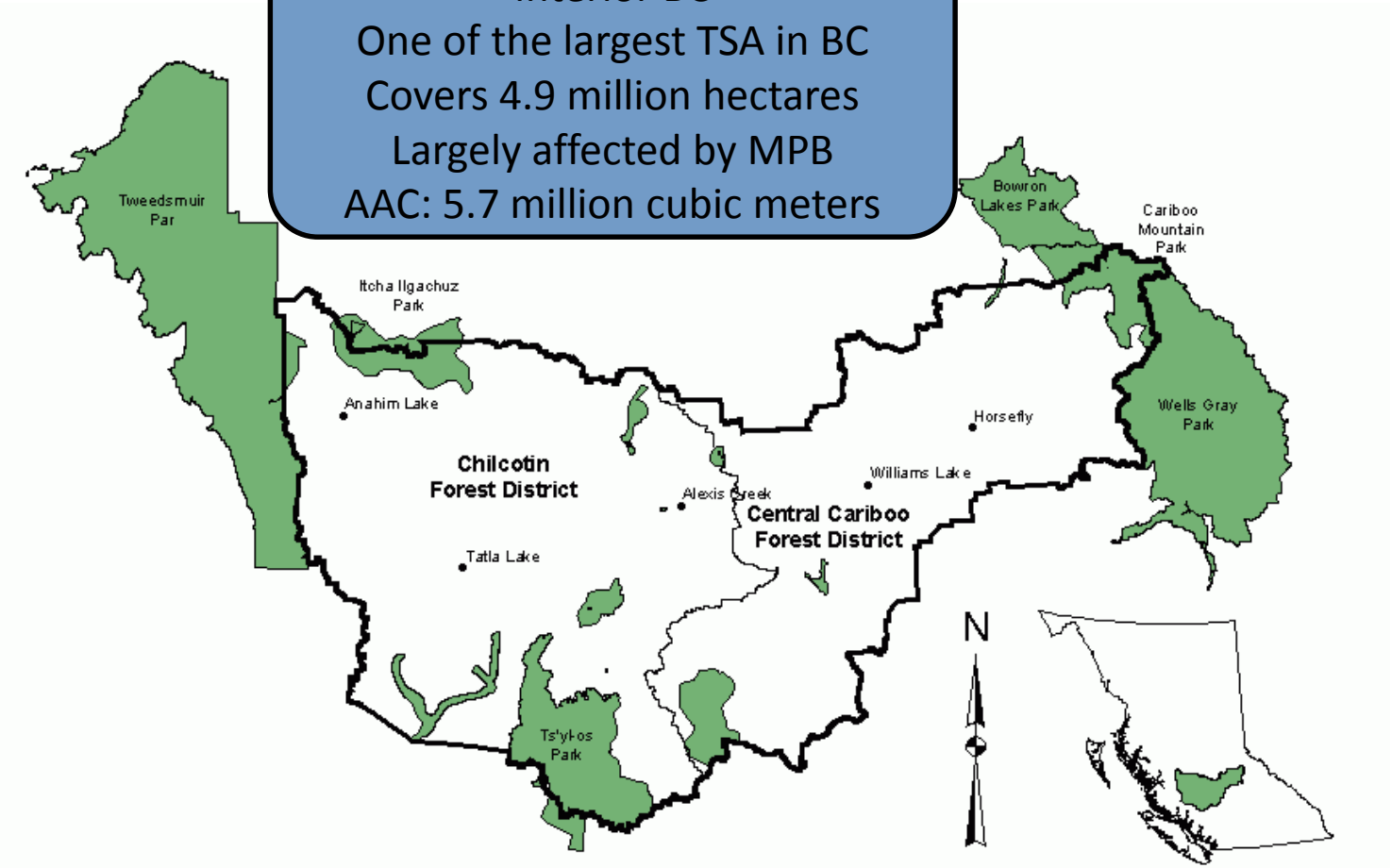
Multi-objective models

Type of objectives	Studies	Remarks
Economic & environmental	Kanzian et al. (2013), Pérez-Fortes et al. (2014), You and Wang (2011), Santibañez-Aguilar et al. (2011), Yue et al. (2013).	• Focused on either bioenergy or biofuels. • Environmental objective was to minimize GHG emissions, environmental footprints or LCA indicators.
Economic, environmental & social	Santibañez-Aguilar et al. (2014), You et al. (2012), Yue et al. (2014), Čuček et al. (2012).	• Social objectives were to minimize land converted from food to energy, or maximize job creation.

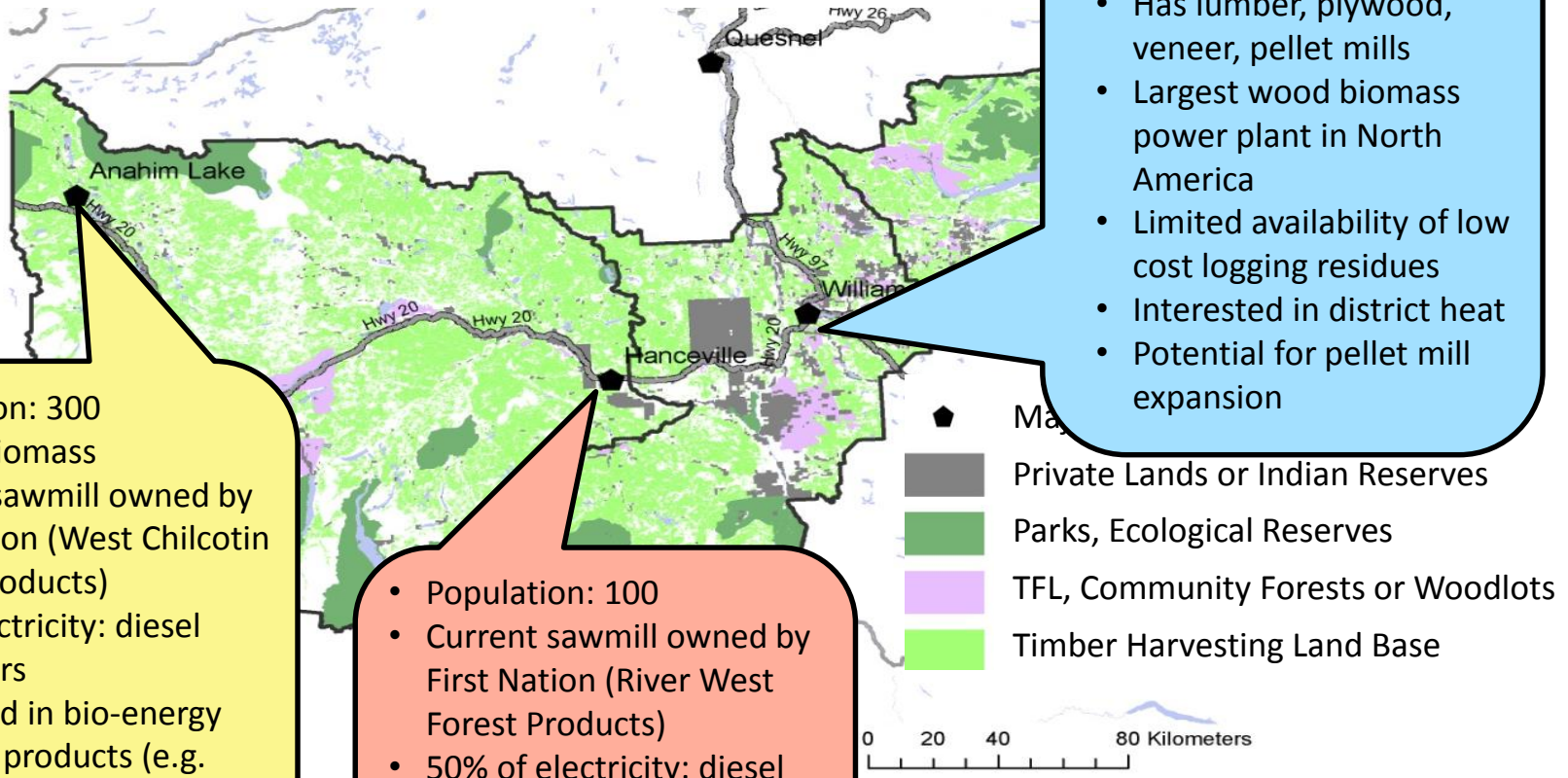
- Most models focused on either bioenergy or biofuel production separately.
- Job creation objectives used multipliers and assumed same level of impact for all of jobs in all locations.

Case study: Williams Lake Timber Supply Area (TSA)

Interior BC
One of the largest TSA in BC
Covers 4.9 million hectares
Largely affected by MPB
AAC: 5.7 million cubic meters



Case study: Williams Lake Timber Supply Area (TSA)



- Population: 12,000
- Has lumber, plywood, veneer, pellet mills
- Largest wood biomass power plant in North America
- Limited availability of low cost logging residues
- Interested in district heat
- Potential for pellet mill expansion

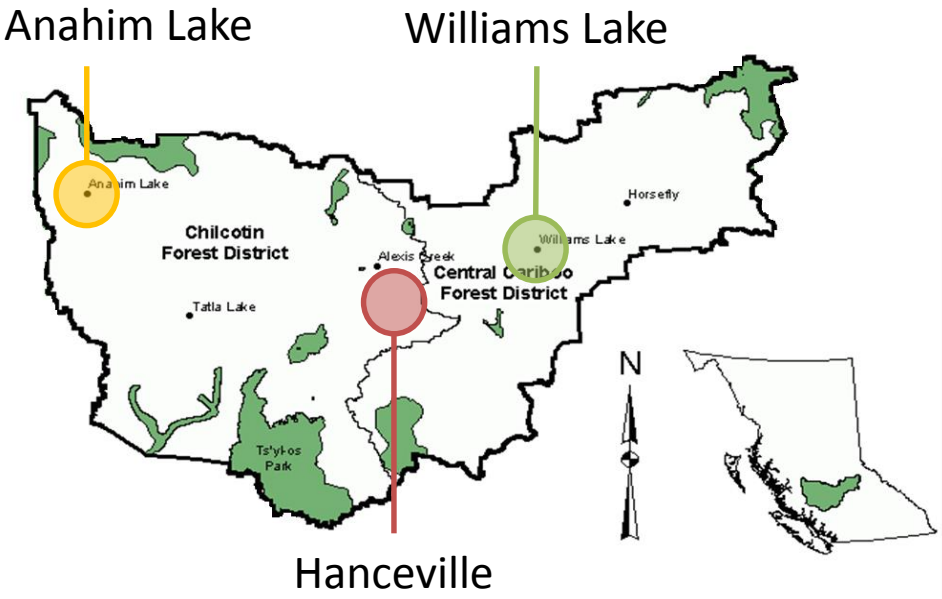
- Population: 300
- Lots of biomass
- Current sawmill owned by First Nation (West Chilcotin Forest Products)
- Local electricity: diesel generators
- Interested in bio-energy and new products (e.g. pyrolysis, pellets)

- Population: 100
- Current sawmill owned by First Nation (River West Forest Products)
- 50% of electricity: diesel generators
- Interested in bio-energy and new products (e.g. pellets)

n_pine_beetle/
ake%20TSA.pdf

Case study

Williams Lake TSA



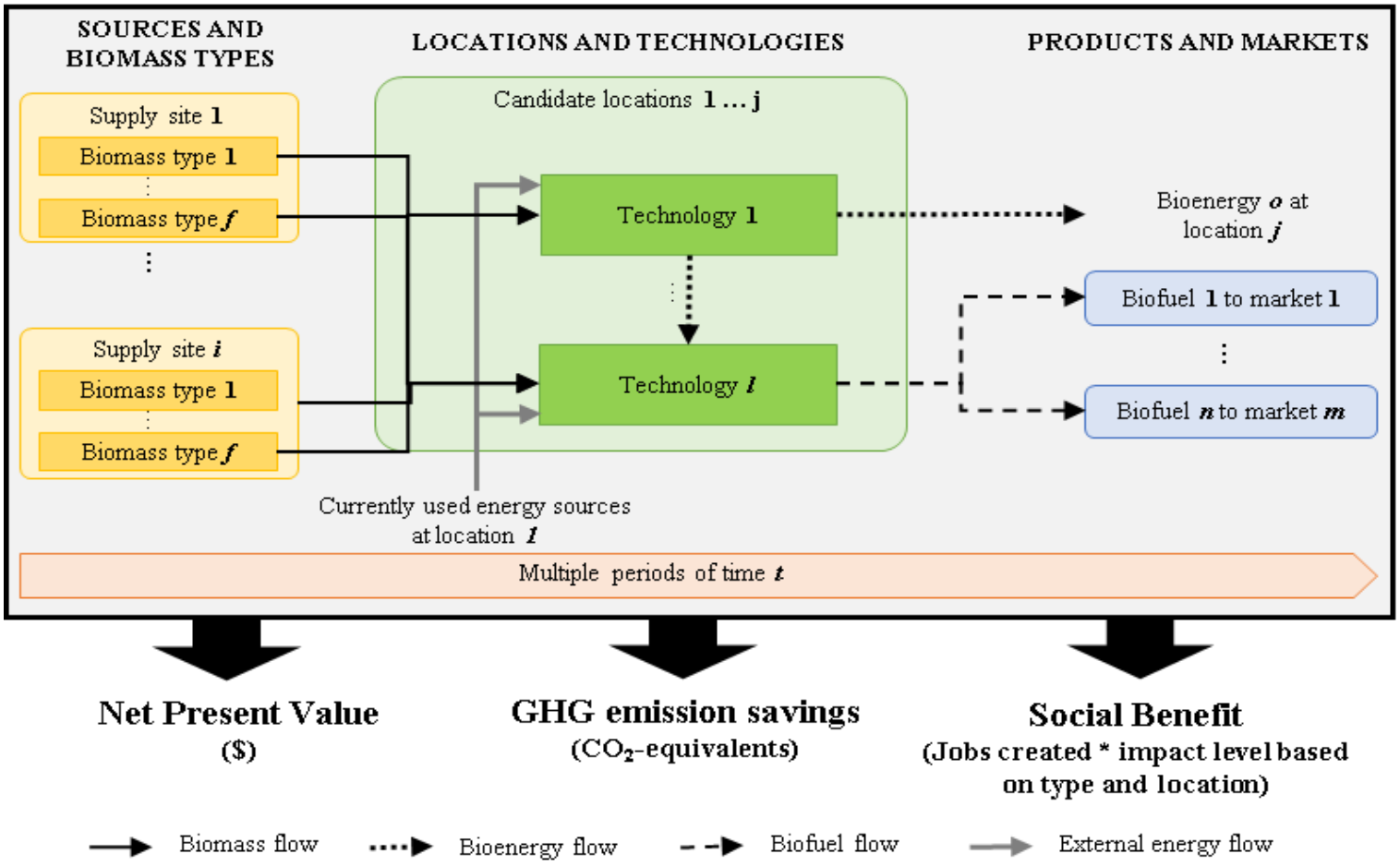
End use of products

- Pellets – coal cofiring
- Bio-oil – industrial heating
- Electricity – replace diesel and BC grid
- Heat – replace heating oil and natural gas

Supply chain alternatives

- **3 plant locations**
- **4 feedstock types**
  MPB logs, logging residues, wood chips, hog fuel
- **1595 Biomass sources**
  1592 forest blocks, 3 sawmills
- **23 technologies/sizes**
  Combustion, gasification, pyrolysis, pellets
- **4 products**
  Electricity, heat, bio-oil, pellets
- **4 markets**
  Including biofuel export
- **20 time periods**

Supply chain design problem



Optimization constraints

$$\sum_{j \in J} B_{f,i,j,t} \leq \beta_{f,i,} \quad \forall \; f \in F, i \in I, t \in T$$

Amount of biomass available is restricted per type, source and period

$$\sum_{I \in I} B_{f,I,j,t} = \sum_{l \in L} U_{f,j,l,t} \qquad \forall \, f \in F, j \in J, t \in T$$

All biomass must be used within the same period (year)

$$P^{Bf}_{n,j,l,t} = \sum_{f \in F} \left(\delta^{Bf}_{n,f,l} \times U_{f,j,l,t}\right) \forall \, n \in N, j \in J, l \in L, t \in T$$

$$P^{Be}_{o,j,l,t} = \sum_{f \in I} \left(\delta^{Be}_{o,f,l} \times U_{f,j,l,t}\right) \forall \, o \in O, j \in J, l \in L, t \in T$$

Production **yield** per product, technology and biomass type

$$P^{Bf}_{n,j,l,t} \leq \gamma^{Bf}_{l,n} \times Q_{j,l,t} \quad \forall \; n \in N, j \in J, l \in L, t \in T$$

$$P^{Be}_{o,j,l,t} \leq \gamma^{Be}_{l,o} \times Q_{j,l,t} \quad \forall \; o \in O, j \in J, l \in L, t \in T$$

Maximum **capacity** of each technology (output capacity)

Optimization constraints

$$\sum_{m \in M} S^{Bf}_{n,j,m,t} \leq \sum_{l \in L} P^{Bf}_{n,j,l,t} \quad \forall\, j \in J, n \in N, t \in T$$

$$S^{Be,Ext}_{o,j,t} + S^{Be,Conv}_{o,j,t} \leq \sum_{l \in L} P^{Be}_{o,j,l,t} \quad \forall\, o \in O, j \in J, t \in T$$

Flow conservation, products generated vs. sold and used

$$\eta^{BfMin}_{n,m,t} \leq \sum_{j \in J} S^{Bf}_{n,j,m,t} \leq \eta^{BfMax}_{n,m,t} \quad \forall\, n \in N, m \in M, t \in T$$

$$\eta^{BeMin}_{o,j,t} \leq S^{Be,Ext}_{o,j,t} \leq \eta^{BeMax}_{o,j,t} \quad \forall\, o \in O, j \in J, t \in T$$

Demand for biofuels and bioenergy per type, market and period

$$\sum_{f \in F} \sum_{l \in L} \left(\phi^{Conv}_{o,f,l} \times U_{f,j,l,t} \right) = S^{Be,Conv}_{o,j,t} + E^{Conv}_{o,j,t} \quad \forall\, o \in O, j \in J, t \in T$$

Energy requirements can be met by generated bioenergy and currently used sources

$$Q_{j,l,t} \geq Q_{j,l,t-1} \quad \forall\, l \in L, j \in J, t \in T$$

Plants must remain **installed over entire planning horizon**

+ Non-negativity and binary constraints

Economic objective function

Maximize the NPV:

$$\mathrm{NPV} = \sum_{t} \frac{1}{(1+\alpha)^{t-1}} \left(\text{Total revenue}_t - \text{Total cost}_t\right)$$

Where:

Revenue from biofuels

Revenue from bioenergy

$$\text{Total revenue}_t = \sum_{n\in N}\sum_{j\in J}\sum_{m\in M}\left(\rho^{Bf}_{n,m,t} \times S^{Bf}_{n,j,m,t}\right) + \sum_{o\in O}\sum_{j\in J}\left(\rho^{Be}_{o,j,t} \times S^{Be,Ext}_{o,j,t}\right) \quad \forall\, t \in T$$

Biomass procurement and transportation costs

Biofuel transportation costs

$$\text{Total cost}_t = \sum_{f\in F}\sum_{i\in I}\sum_{j\in J}\left(\lambda^{Bm}_{f,i,t} \times B_{f,i,j,t}\right) + \sum_{f\in F}\sum_{i\in I}\sum_{j\in J}\left(\lambda^{Tra,Bm}_{f,i,j,t} \times B_{f,i,j,t}\right)$$

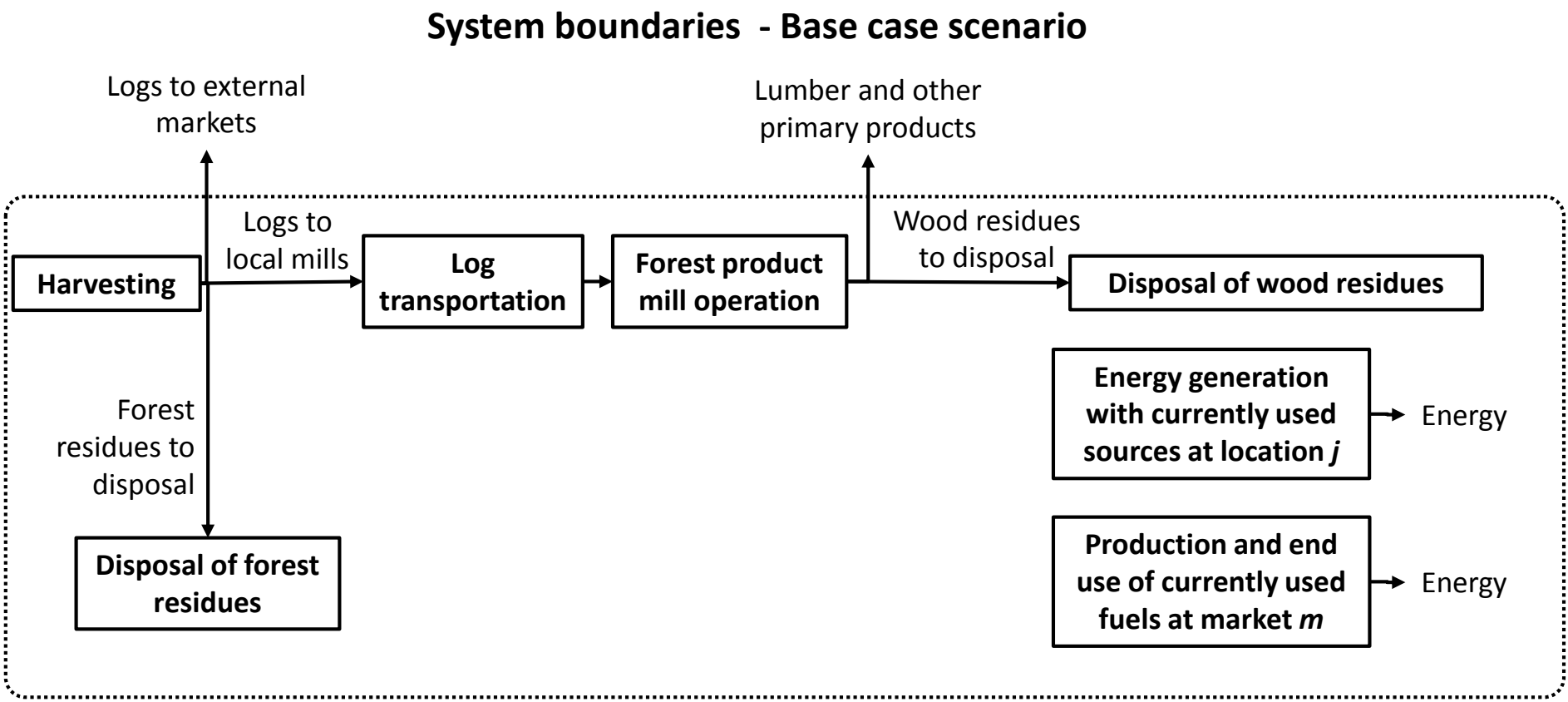
$$+ \sum_{n\in N}\sum_{m\in M}\sum_{j\in J}\left(\lambda^{Tra,Bf}_{n,j,m,t} \times S^{Bf}_{n,j,m,t}\right) + \sum_{l\in L}\sum_{j\in J}\left(\lambda^{Fix}_{j,l,t} \times Q_{j,l,t}\right) + \sum_{f\in F}\sum_{j\in J}\sum_{l\in L}\left(\lambda^{Var}_{j,l,t} \times U_{f,j,l,t}\right)$$

Fixed and variable operating costs

$$+ \sum_{o\in O}\sum_{j\in J}\left(\lambda^{Energy}_{o,j,t} \times E^{Conv}_{o,j,t}\right) \quad \forall\, t \in T$$

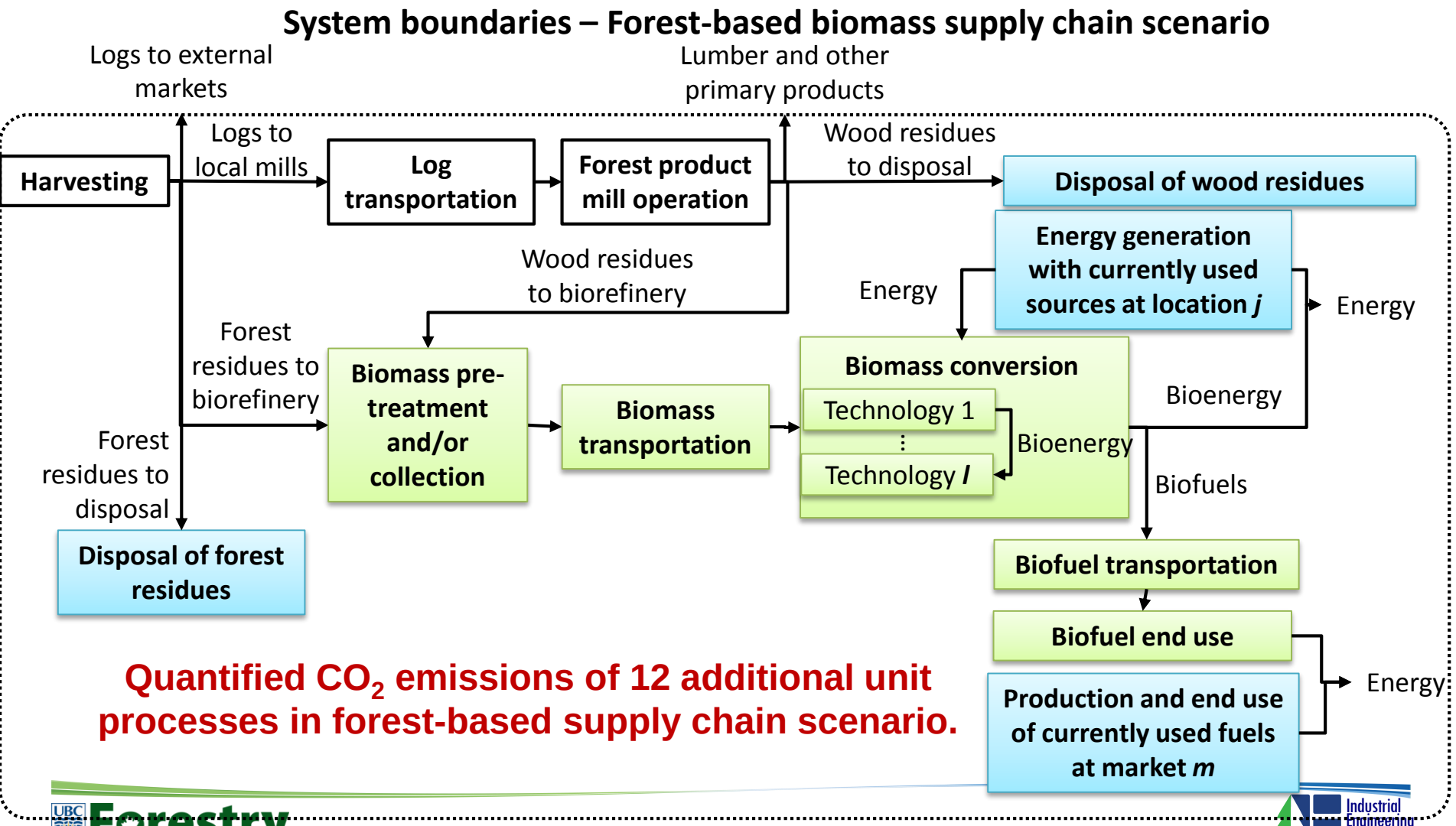
Energy costs

Life cycle GHG analysis



Quantified CO_2 emissions of 17 unit processes in base case scenario.

Life cycle GHG analysis



Quantified CO_2 emissions of 12 additional unit processes in forest-based supply chain scenario.

Environmental objective function

Maximize the GHG emission savings:

$$\text{GHG emission savings} = \textit{Avoided GHG} - \textit{Forest biomass supply chain GHG}$$

Where:

$$\textit{Avoided GHG} = \sum_{o\in O}\sum_{j\in J}\sum_{t\in T}\left(e_{o,j}^{Energy} \times S_{o,j,t}^{Be,Ext}\right) + \sum_{n\in N}\sum_{m\in M}\sum_{j\in J}\sum_{t\in T}\left(e_{n,m}^{Fuel} \times S_{n,j,m,t}^{Bf}\right) + \sum_{f\in F}\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\left(e_{i,f}^{Disp} \times B_{f,i,j,t}\right)$$

Energy substitution

Fuel substitution

Diversion of biomass from disposal as waste

$$\textit{Forest biomass supply chain GHG} = \sum_{f\in F}\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\left(e_{i,f}^{Bm} \times B_{f,i,j,t}\right) + \sum_{f\in F}\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\left(e_{f,i,j}^{Tra,Bm} \times B_{f,i,j,t}\right) + \sum_{n\in N}\sum_{j\in J}\sum_{m\in M}\sum_{t\in T}\left(e_{n,j,m}^{Tra,Bf} \times S_{n,j,m,t}^{Bf}\right) + \sum_{f\in F}\sum_{j\in J}\sum_{l\in L}\sum_{t\in T}\left(e_{l}^{Conv} \times U_{f,j,l,t}\right) + \sum_{o\in O}\sum_{j\in J}\sum_{t\in T}\left(e_{o,j}^{Energy} \times E_{o,j,t}^{Conv}\right)$$

Biomass production and transportation

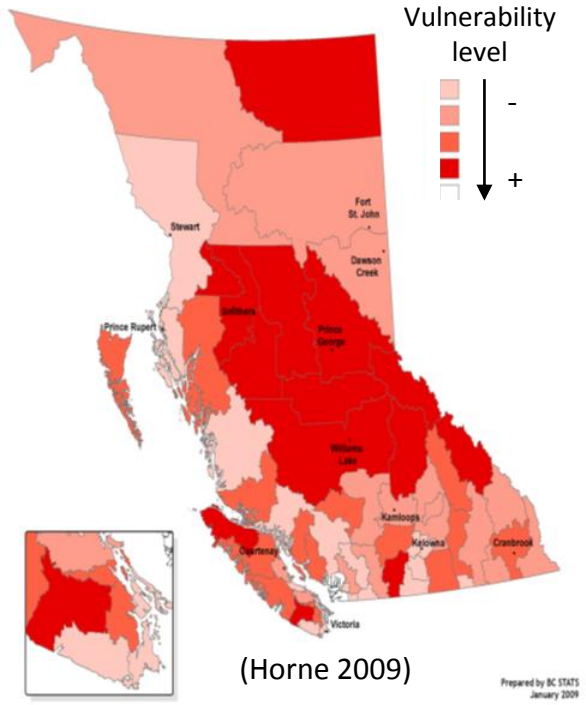
Biofuel transportation

Conversion

Energy used in conversion

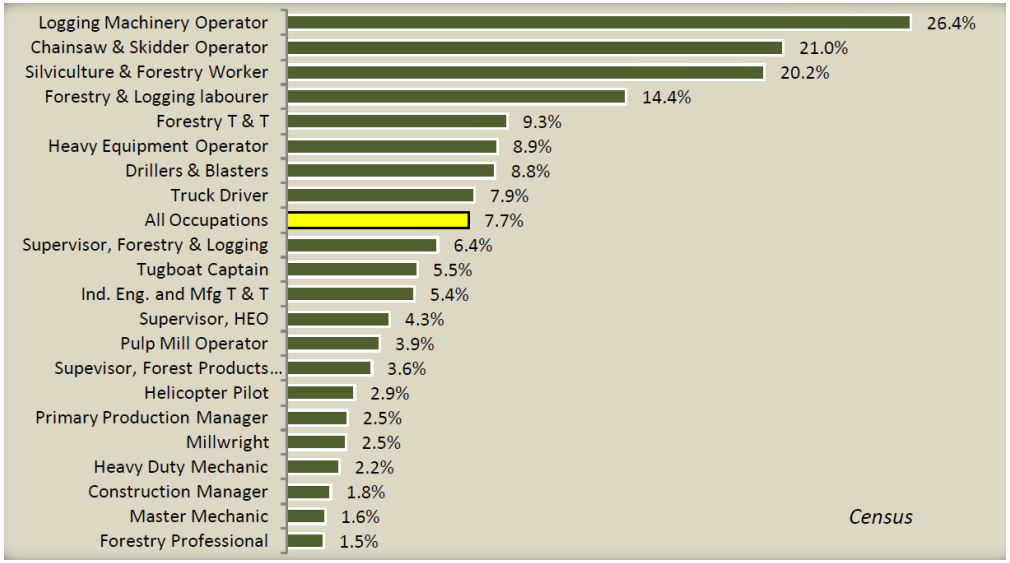
Social benefit of job creation in BC

Different regions:
different **forest vulnerability levels**



(Horne 2009)

Different occupations:
different **unemployment rates**



(LMI Insight and R.A. Malatest & Associates Ltd, 2013)

$$\chi_{v,j} = Forest\ vulnerability\ index_j * Average\ unemployment\ rate_v$$

Social objective function

Maximize the social benefit:

$$Social\ benefit = \sum_{v \in V} \sum_{j \in J} \left(\left(Hours_{v,j}^{Bm} + Hours_{v,j}^{Conv,Salary} + Hours_{v,j}^{Conv,Hourly} + Hours_{v,j}^{Constr} \right) \times \chi_{v,j} \right)$$

Social benefit factor (job class *v* at location *j*)

Where:

$$Hours_{v,j}^{Bm} = \sum_{f \in F} \sum_{i \in I} \sum_{t \in T} \left(w_{v,f,i}^{Bm} \times B_{f,i,j,t} \right) \ \forall\, v \in V, j \in J$$

Hours of work for biomass production

$$Hours_{v,j}^{Conv,Hourly} = \sum_{f \in F} \sum_{l \in L} \sum_{t \in T} \left(w_{v,l}^{Conv,Hourly} \times U_{f,j,l,t} \right) \ \forall\, v \in V, j \in J$$

Hours of wage work for conversion

$$Hours_{v,j}^{Conv,Salary} = \sum_{l \in L} \sum_{t \in T} \left(w_{v,l}^{Conv,Salary} \times Q_{j,l,t} \right) \ \forall\ v \in V, j \in J$$

Hours of salaried work for conversion plants

$$Hours_{v,j}^{Constr} = \sum_{l \in L} \left(w_{v,l}^{Constr} \times \sum_{t \in T} \left(Q_{j,l,t} - Q_{j,l,t-1} \right) \right) \ \forall\, v \in V, j \in J$$

Hours of work for plant construction

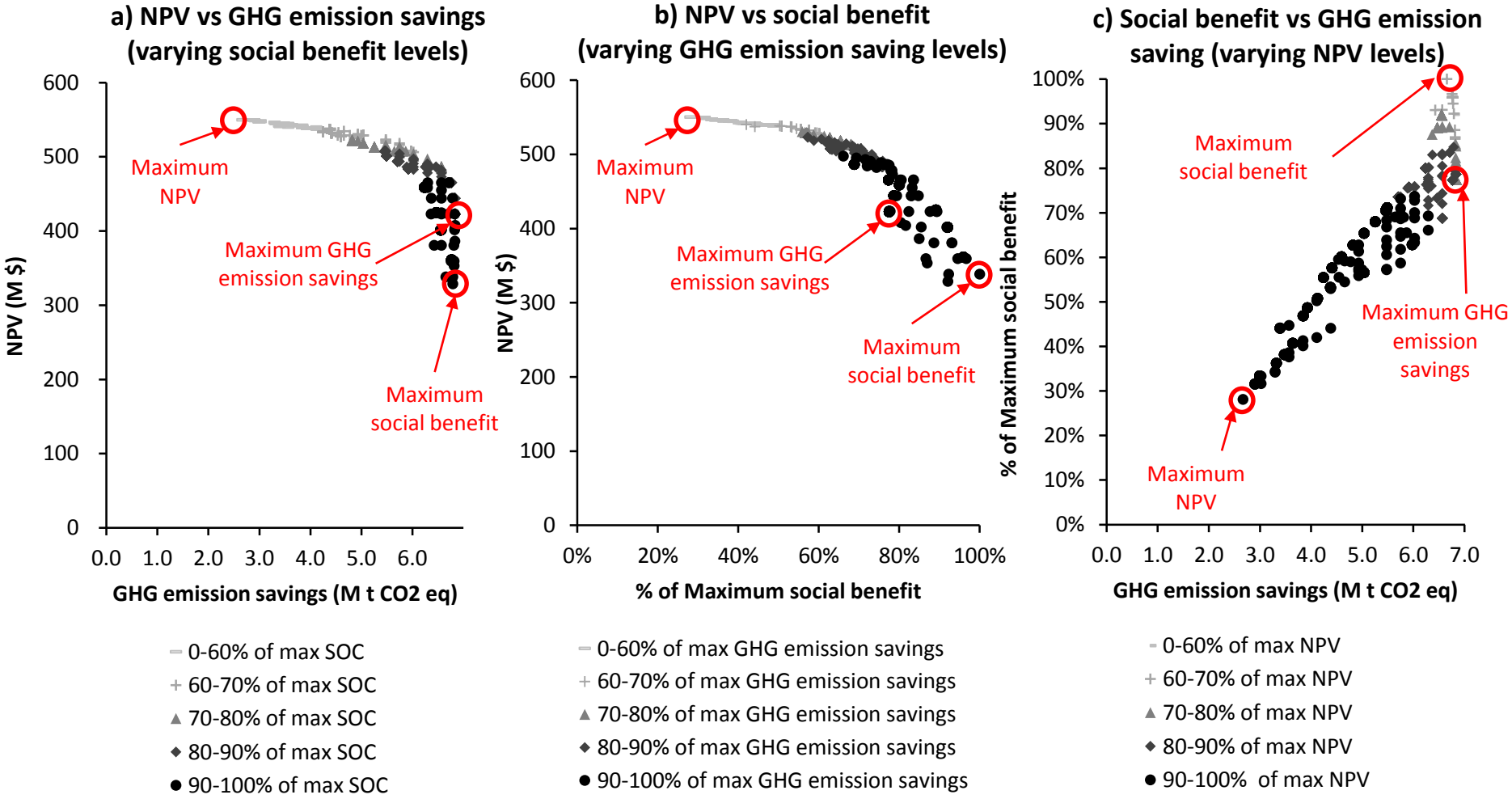
NOTE: Transportation-related jobs are estimated by the model, but are not considered within the social objective function to be maximized.

Solution for single objectives

	Maximum NPV	Maximum GHG emission savings	Maximum social benefit
NPV	550 M$	424 M$	330 M$
GHG emission savings	2.67 M t CO_2-eq	6.84 M t CO_2-eq	6.79 M t CO_2-eq
Social benefit (created jobs)	13 M points (82 jobs)	36 M points (203 jobs)	43 M points (238 jobs)

Technologies	Maximum NPV	Maximum GHG emission savings	Maximum social benefit
Anahim Lake			
Biomass boiler + steam turbine (heat and electricity), 5 MW	period 1		
Biomass oil heater + ORC (heat and electricity), 5 MW		period 1	period 1
Pellet plant, 45,000 t/year		period 1	period 1
Hanceville			
Biomass boiler + steam turbine (electricity only), 0.5 MW	period 1		
Biomass boiler + steam turbine (heat and electricity), 5 MW		period 1	
Biomass oil heater + ORC (heat and electricity), 5 MW			period 1
Pellet plant, 45,000 t/year		period 1	period 1
Pyrolysis plant, 200 odt/day			
Pyrolysis plant, 400 odt/day	period 1		
Williams Lake			
Biomass boiler (heat only), 2 MW	period 1		
Biomass oil heater + ORC (heat and electricity), 2 MW		period 1	
Biomass oil heater + ORC (heat and electricity), 5 MW			period 1
Biomass boiler + steam turbine (heat and electricity), 2 MW			
Pellet plant, 15,000 t/year	period 1		
Pellet plant, 45,000 t/year		period 1	period 1
Pyrolysis plant, 200 odt/day			
Pyrolysis plant, 400 odt/day		period 1	period 1

Multi-objective optimization of case study



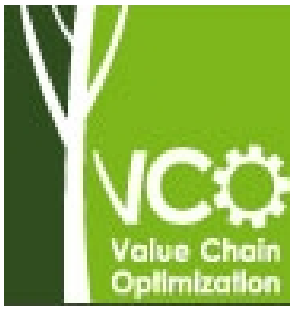
Conclusions

- Developed optimization model for forest-based biomass supply chains with economic, environmental and social objectives
- Bio-oil seems most profitable option but its market is incipient.
- Bioenergy in off-grid communities is advisable.
- Pellets generate large GHG savings but low NVP.
- Trade-off between NPV and social/environmental benefit.
- Decision makers can choose the best solution based on their preferences.

Acknowledgement

FPInnovations

CONACYT



NSERC
CRSNG

Cited references

- Horne, G., 2009. 2006 Economic dependency tables for forest districts. Ministry of Management Services, BC Stats, Victoria.
- Čuček, L., Varbanov, P.S., Klemeš, J.J., Kravanja, Z., 2012. Total footprints-based multi-criteria optimisation of regional biomass energy supply chains. Energy 44 (1), 135–145.
- Ekşioğlu, S.D., Acharya, A., Leightley, L.E., Arora, S., 2009. Analyzing the design and management of biomass-to-biorefinery supply chain. Computers & Industrial Engineering 57 (4), 1342–1352.
- Elia, J.A., Baliban, R.C., Xiao, X., Floudas, C.A., 2011. Optimal energy supply network determination and life cycle analysis for hybrid coal, biomass, and natural gas to liquid (CBGTL) plants using carbon-based hydrogen production. Comput. Chem. Eng. 8, 1399-1430
- Feng, Y., D'Amours, S., LeBel, L., & Nourelfath, M. (2010). Integrated bio-refinery and forest products supply chain network design using mathematical programming approach. (No. 50). Montreal: CIRRELT.
- Freppaz, D., Minciardi, R., Robba, M., Rovatti, M., Sacile, R., & Taramasso, A. (2004). Optimizing forest biomass exploitation for energy supply at a regional level. Biomass and Bioenergy, 26(1), 15-25.
- Frombo, F., Minciardi, R., Robba, M., Rosso, F., Sacile, R., 2009a. Planning woody biomass logistics for energy production: A strategic decision model. Biomass Bioenergy. 3, 372-383
- Frombo, F., Minciardi, R., Robba, M., Sacile, R., 2009b. A decision support system for planning biomass-based energy production. Energy. 3, 362-369
- Kanzian, C., Kühmaier, M., Zazgornik, J., Stampfer, K., 2013. Design of forest energy supply networks using multi-objective optimization. Biomass Bioenergy. 0, 294-302
- Kim, J., Realff, M.J., Lee, J.H., Whittaker, C., Furtner, L., 2011. Design of biomass processing network for biofuel production using an MILP model. Biomass & Bioenergy. 2, 853-871

Cited references

- Leduc, S., Schwab, D., Dotzauer, E., Schmidt, E., Obersteiner, M., 2008. Optimal location of wood gasification plants for methanol production with heat recovery. International Journal of Energy Research 32 (12), 1080–1091.
- LMI Insight and R.A. Malatest & Associates Ltd, 2013. British Columbia forest sector: labour market and training needs assessment. Prepared for BC Coastal Forest Industry, Labour Market Information Working Group.
- Natarajan, K., Leduc, S., Pelkonen, P., Tomppo, E., Dotzauer, E., 2014. Optimal locations for second generation Fischer Tropsch biodiesel production in Finland. Renewable Energy 62, 319–330.
- Parker, N., Tittmann, P., Hart, Q., Nelson, R., Skog, K., Schmidt, A., Gray, E., Jenkins, B., 2010. Development of a biorefinery optimized biofuel supply curve for the Western United States. Biomass Bioenergy. 11, 1597-1607
- Pérez-Fortes, M., Laínez-Aguirre, J.M., Bojarski, A.D., Puigjaner, L., 2014. Optimization of pre-treatment selection for the use of woody waste in co-combustion plants. Chem. Eng. Res. Design. 8, 1539-1562
- Santibañez-Aguilar, J.E., González-Campos, J.B., Ponce-Ortega, J., Serna-González, M., El-Halwagi, M., 2011. Optimal Planning of a Biomass Conversion System Considering Economic and Environmental Aspects. Ind Eng Chem Res. 14, 8558-8570
- Santibañez-Aguilar, J.E., González-Campos, J.B., Ponce-Ortega, J.M., Serna-González, M., El-Halwagi, M.M., 2014. Optimal planning and site selection for distributed multiproduct biorefineries involving economic, environmental and social objectives. J. Clean. Prod. 0, 270-294
- Schmidt, J., Leduc, S., Dotzauer, E., Kindermann, G., Schmid, E., 2010. Potential of biomass-fired combined heat and power plants considering the spatial distribution of biomass supply and heat demand. International Journal of Energy Research. 11, 970-985

Cited references

- Tittmann, P.W., Parker, N.C., Hart, Q.J., Jenkins, B.M., 2010. A spatially explicit techno-economic model of bioenergy and biofuels production in California. J. Transp. Geogr. 6, 715-728
- You, F., & Wang, B. (2011). Life cycle optimization of biomass-to-liquid supply chains with distributed–centralized processing networks. Industrial & Engineering Chemistry Research, 50(17), 10102-10127.
- You, F., Tao, L., Graziano, D.J., Snyder, S.W., 2012. Optimal design of sustainable cellulosic biofuel supply chains: Multiobjective optimization coupled with life cycle assessment and input–output analysis. AIChE Journal. 4, 1157-1180
- Yue, D., Kim, M.A., You, F., 2013. Design of Sustainable Product Systems and Supply Chains with Life Cycle Optimization Based on Functional Unit: General Modeling Framework, Mixed-Integer Nonlinear Programming Algorithms and Case Study on Hydrocarbon Biofuels. ACS Sustainable Chemistry & Engineering. 8, 1003-1014
- Yue, D., Slivinsky, M., Sumpter, J., You, F., 2014. Sustainable Design and Operation of Cellulosic Bioelectricity Supply Chain Networks with Life Cycle Economic, Environmental, and Social Optimization. Industrial & Engineering Chemistry Research. 10, 4008-4029

Thank you

Taraneh Sowlati
taraneh.Sowlati@ubc.ca