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Biomass transport for energy in Switzerland:

Costs, energy and CO_2 performance of main forest wood and manure transport chains

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Zusammenfassung

Die Transportkosten haben einen bedeutenden Anteil am Endpreis von Biomasse für energetische Zwecke. Zudem benötigt der Transport Energie und ist für Treibhausgasemissionen verantwortlich. Wir führen eine techno-ökonomische Analyse des Biomasse-Transports für die wichtigsten Waldholzprodukte in der Schweiz (Stückholz und Hackschnitzel) sowie für Gülle und Mist durch. In einem ersten Schritt werden mit Hilfe von Interviews, die dem Ansatz von *Mental Models* folgen, die in der Schweiz am häufigsten Transportwege vom Lieferanten bis zum Endverbraucher ermittelt. Unseres Wissens sind Mentale Modelle im Zusammenhang mit Logistikketten noch nie eingesetzt worden. Wir schlagen deshalb eine Methodik vor, die auf elegante Art und Weise den Standpunkt der verschiedenen Interessengruppen erfasst. Sie eignet sich insbesondere dann, wenn die aktuellen Transportpraktiken nicht dokumentiert oder unbekannt sind. Für 12 identifizierte Transportketten werden Kosten, Energie und CO_2-Emissionen quantifiziert. Für jede Transportkette werden die Einnahmen in Bezug zu den Kosten gesetzt, der Primärenergieinhalt der Ressource zum tatsächlichen Energieaufwand, ebenso wie die CO_2-Emissionen fossiler Energiequellen zu den tatsächlichen Emissionen. Diese drei Indikatoren charakterisieren jede einzelne Transportkette.

In der Schweiz erfolgt der Transport der Biomasse hauptsächlich auf der Strasse über Entfernungen von 1 bis 30 km. Die Ergebnisse zeigen, dass der Transport von Waldhackschnitzel effizienter ist als der Transport von Stückholz, und dass sich Mist besser transportieren lässt als Gülle, ausser wenn unterirdische Gülleleitungen verwendet werden. Im Fall der Schweiz sind die Haupthindernisse für den Transport von Biomasse eher die Kosten als der Energieaufwand oder die CO_2-Emissionen. Das Be- und Entladen der Ressource macht einen bedeutenden Anteil der Endleistung aus, da sie bis zu 56% der gesamten Transportkosten ausmachen kann. Die Energie, die benötigt wird, um das Waldholz an die Endverbraucher zu liefern, macht zwischen 0.3% und 1.8% der darin enthaltenen Primärenergie aus, im Falle von Gülle sind es weniger als 5%. Einige Transportketten für Waldholz erreichen die maximale kostendeckende Transportentfernung nach 43 km, während sie für andere mehr als 400 km betragen kann. Im Extremfall sollte die Transportentfernung von Gülle unter Kostengesichtspunkten nicht mehr als 3 km betragen. Würde man jedoch nur den im Treibstoff enthaltenen Energieaufwand und die entsprechenden CO_2-Emissionen berücksichtigen, lägen die Schwellenentfernungen zwischen 145 und über tausend Kilometer. In unserer Analyse erlaubt die Verwendung von landwirtschaftlichen Rohstoffen eine bis zu 3-fache Kompensation der Energie des Transports, wobei sehr konservative Methanemissionen bei der Biogasproduktion berücksichtigt werden. Dies zeigt, dass die Kosten das Haupthindernis für den Transport von Biomasse zur Energiegewinnung sind und unterstreicht die Relevanz ihrer Verwendung zur Bewältigung der aktuellen Umweltprobleme. Die Ergebnisse können als Ausgangspunkt für vertiefte Untersuchungen von Biomasse-Logistikketten dienen, zur Identifizierung optimaler Anlagenstandorte genutzt werden und auf lokaler Ebene Entscheidungsträgern und Praktikern nützliche Erkenntnisse liefern.

Résumé

Le transport de la biomasse représente une part importante du prix final de la biomasse utilisée à des fins énergétiques et le transport lui-même nécessite d'importantes quantités d'énergie et est responsable d'émissions de gaz à effet de serre. Nous réalisons une analyse technico-économique du transport de la biomasse pour les principaux bois de forêts en Suisse (bois de chauffage et copeaux de bois), ainsi que pour le fumier et le lisier. La première étape consiste à identifier les chaînes logistiques les plus utilisées du fournisseur au consommateur final, à l'aide d'entretiens qui suivent une approche dite de *Mental Models*. À notre connaissance, les Modèles Mentaux n'ont jamais été utilisés dans le contexte des chaînes logistiques. Permettant de saisir avec élégance le point de vue des différents acteurs, cette méthodologie est applicable lorsque les pratiques actuelles de transport sont non-documentées ou inconnues. Ensuite, les 12 chaînes de transport identifiées sont quantifiées en terme de coût, de besoins énergétiques et d'émissions de CO_2. Pour chaque chaîne de transport, les revenus sont comparés aux coûts de transport, l'énergie primaire contenue dans la ressource au besoin énergétique de son transport et les émissions de CO_2 évitées par la consommation d'énergie de source fossile au CO_2 émit lors du transport.

En Suisse, le transport se fait principalement par route sur des distances allant de 1 à 30 km. Les résultats montrent que le transport des plaquettes de bois est plus performant que le transport des bois de chauffage et que le transport de fumier est plus intéressant que celui du lisier, sauf lorsque des canalisations souterraines sont utilisées. Dans le cas de la Suisse, le principal obstacle au transport de la biomasse est le coût plutôt que les impacts énergétiques ou environnementaux. Le chargement et le déchargement des ressources représentent une part importante de la performance finale, puisqu'ils peuvent représenter jusqu'à 56% du coût total du transport. Les besoins énergétiques pour livrer le bois de forêt aux consommateurs finaux représente entre 0,3% et 1,8% de l'énergie primaire qu'il contient, et moins de 5% dans le cas des engrais de ferme. Certaines chaînes logistiques de bois de forêt atteignent le seuil de rentabilité maximum après 43 km seulement, tandis que d'autres peuvent atteindre plus de 400 km. En ce qui concerne les coûts, le transport agricole du lisier ne devrait pas dépasser 3 km. Cependant, si l'on ne considère que l'énergie contenue dans le carburant utilisé et les émissions de CO_2 qui en découlent, les distances seuils se situeraient entre 145 et plus de mille kilomètres. Dans notre analyse, l'utilisation des engrais de ferme permet de compenser jusqu'à 3 fois l'énergie de son transport, tout en considérant des émissions de méthane importantes lors de la production de biogaz. Cela démontre que le coût est le principal obstacle au transport de la biomasse à des fins énergétiques et souligne la pertinence de son utilisation pour relever les défis environnementaux actuels. Les résultats peuvent servir de point de départ à des enquêtes plus approfondies sur les chaînes logistiques de la biomasse, être utilisés pour identifier les emplacements optimaux des installations de transformation énergétiques et fournir, au niveau local, des informations utiles aux décideurs et aux praticiens.

Summary

Biomass transport represents a significant share of the final price of biomass for energy purpose and transport itself requires energy and is responsible for greenhouse gas emissions. We conduct a techno-economic analysis of biomass transport for the main forest wood products in Switzerland (firewood and woodchips), as well as for solid and liquid manure. The first step is to identify the most widely used transport chains from the supplier to the final consumer in Switzerland, using interviews that follow a *Mental Models* approach. To our knowledge, Mental Models have never been used in the context of logistics chains. Allowing to elegantly capture the point of view of different stakeholders, we therefore, propose a methodology which is applicable when transport current practices are undocumented or unknown. For the 12 identified transport chains of these different types of biomass, we quantify the cost, energy input, and CO_2 emissions. For each transport chain, the income from the resource is compared to the transport costs, its primary energy contained to the actual energy input and the avoided CO_2 emissions from using substitute fossil energy source to the actual emissions of transport.

In Switzerland, transport mainly occurs by road on distances ranging from 1 to 30 km. Results show that transport of woodchips is more performant than transport of firewood, and that solid manure is more interesting that liquid manure, except when underground slurry pipes are used. In the case of Switzerland, the main barrier to biomass transport is cost rather than energy or environmental impacts. Loading and unloading the resource represent a significant share of the final performance, as it can account for up to 56% of total transport costs. Energy required to deliver the forest wood to final consumers represents between 0.3% and 1.8% of the primary energy contained in it, and less than 5% in the case of manure. Some forest wood chains attain the maximum break-even transport distances after 43 km only, whereas others can reach over 400 km. Using agricultural transport for slurry should not exceed 3 km when it comes to costs. However, if only direct energy inputs and CO_2 emissions were to be considered, threshold distances would be between 145 to over thousand km. In our analysis, using agricultural feedstock allows to compensate up to 3 time the energy of its transport, whilst considering very conservative methane emissions during biogas production. This demonstrates that cost is the main barrier to transporting biomass for energy and highlights the relevance of its use to tackle current environmental challenges. The results can serve as a start for deeper investigations of biomass logistics chains, be used to identify optimal plant locations and provide, at a local level, useful insights to decision-makers and practitioners.

Main findings

- Transport distances for firewood range between 1 and 15 km to the final consumer, and woodchips between 5 and 30 km. Liquid manure is transported on average on 5 km, solid manure on 9 km and fermentation slurry on 7 km.
- Woodchips transport is more efficient than firewood in terms of costs, energy and CO_2 emissions, except for highly professionalized firewood transporters.
- The main barrier to forest wood and manure transport is the cost, followed to a lesser extent by CO_2 emissions.
- Maximum transport distances of firewood range between 43 and 110 km whereas woodchips can reach up to 477 km. Solid manure between 136 km and 324 km; liquid manure between 3 km and 82 km.

Contents

Abbreviations

AD	Anaerobic Digestion	GHG	Greenhouse gas
C	Chips	LM	Liquid manure
C-F	Woodchips transport chain by farmers	MCF	Methane conversion factor
CH_4	Methane	MJ	Megajoule
CHP	Combined heat and power	MM	Manure management
$C\text{-}P_H$	Woodchips transport chain by professionals (higher level of specialisation)	N_2O	Nitrous oxyde
$C\text{-}P_L$	Woodchips transport chain by professionals (lower level of specialisation)	oDM	Organic Dry Matter
C-WSS	Woodchips transport chain to winter safe storage (optional)	P	Professional
DM	Dry Matter	PJ	Petajoule
$eq\text{-}CO_2$	CO_2 equivalents	RC	Economic indicator
F	Farmer	RCO_2	Environmental indicator
FW	Firewood	RE	Energy Indicator
FW-F	Firewood transport chain by farmers	SM	Solid manure
$FW\text{-}P_H$	Firewood transport chain by professionals (high)	SSWB	Small-scale wood buyer
$FW\text{-}P_L$	Firewood transport chain by professionals (low)	t_{DM}	Tonne of feedstock dry matter
FW-SSWB	Firewood transport chain by small-scale wood buyers	t_{FM}	Tonne of feedstock fresh matter

Glossary

Woodchips: Small-sized pieces of wood from chipping larger pieces of wood. Woodchips can originate from different sources (wood from landscape maintenance, waste wood, wood residues or forest wood). Forest woodchips are produced from energy round wood or waste material, such as branches or bark.

Firewood: Forest wood sliced in pieces of 25 cm to 1 meter that is used in open chimneys or wood ovens.

Manure: Composed of animal faeces and urine and may contain livestock bedding, additional water and wasted feed.

Liquid manure or slurry: Type of livestock waste that is in liquid form, collected in liquid manure pits and usually mixed with water. Before dilutions, liquid manure has a dry matter content between 4% and 9% (GRUDAF, 2009).

Solid manure: Type of livestock waste that is in solid form, collected in the stables, with a dry mass content between 20% and 65% (GRUDAF, 2009)

Fermentation slurry or digestate: Manure that has been through the process of anaerobic digestion in a biogas facility.

Tonne: Also known as a *metric ton*, a tonne is a unit of mass equivalent to 1’000 kilograms. This should not be confused with the American English *ton* which equals 2’000 pounds.

Stere: One cubic meter of piled firewood, equivalent to approx. 0.71 solid m^3 of wood

1 Introduction

1.1 Background information and current situation

Due to their impact on climate, greenhouse gas emissions (GHG) put pressure on the global energy systems. When used sustainably, biomass is carbon neutral and can provide a storable alternative to phase out fossil fuels (Hiloidhari et al., 2019; Sulaiman et al., 2020). With possible applications in electricity, heat, and transport, biomass is also considered an important resource for the Swiss energy transition. With the Energy Strategy 2050 (SFOE, 2018), Switzerland established a framework to increase the use of renewable energy to replace the soon to be retired nuclear power. In 2019, Switzerland also set the goal of carbon neutrality by 2050 (The Federal Council, 2019). With an additional 44.2 PJ that could be sustainably exploited per year, biomass resources in Switzerland could double their contribution by 2050, herewith representing 4% of the country's gross energy consumption (Burg et al., 2018; Thees et al., 2017).

The most significant additional available potential of Swiss biomass is attributed to animal manure (24PJ) (Thees et al., 2017). During the process of anaerobic digestion (AD), the organic matter contained in solid and liquid animal excreta is degraded and transformed into biogas, composed of up to 60% methane (CH_4). The biogas is further used in combined heat and power (CHP) to produce electricity and heat, or can be upgraded to biomethane and injected in the gas grid or used as fuel for vehicles. The gas grid being currently little developed, this latest option is still uncommon in the country (Kaufmann, 2020; SFOE, 2019a). In addition, the CH_4 and nitrous oxide (N_2O) emissions occurring during the storage of manure and representing 19% of the total emission from the agricultural sector in Switzerland (Burg et al., 2018; Thees et al., 2020), could be significantly reduced by AD.

The use of forest wood offers the second-largest additional sustainable primary energy potential, where firewood (FW) or woodchips (C), and recently wood pellets, are the most common types of feedstock. When considering a moderate stock reduction and assuming common silvicultural management strategies, forest wood surpluses could provide additional 9 PJ per year (Thees et al., 2017). Using these creates added-value as forest wood is usually harvested for material purposes and its energetic use can be considered as a valuable by-product. The large availability and suitable properties of woodchips, mainly composed of crown material or less qualitative stem wood, led to a rising number of woodchips heating installations and the construction of large wood based CHP at the expense of firewood stoves (FOEN, 2018; Stettler and Betbèze, 2019).

The complex logistics associated with the transport of forest wood and manure induce economic (Bergström and Fulvio, 2014; Gold and Seuring, 2011; Mele et al., 2011), energetic (Berglund and Börjesson, 2006; Bergström and Fulvio, 2014; Mele et al., 2011) and environmental implications

(Capponi et al., 2012; Delivand et al., 2015; Mele et al., 2011) that can represent a barrier to the development of the biomass sector (Chum et al., 2011; De Meyer et al., 2014; Mele et al., 2011). Characteristics inherent to biomass, such as its variable bulk density and calorific value, result in different needs for space per unit of energy and have a direct negative impact on the processing efficiency of the energy source's logistics chain (Allen et al., 1998; Rentizelas et al., 2009; Wolfsmayr and Rauch, 2014). Transport planning optimization is a key issue of the upstream logistics chain (Bravo et al., 2012; Rentizelas et al., 2009). It begins when loading the feedstock on the vehicle and ends with unloading it at the storage or consumer's location (Rentizelas and Tatsiopoulos, 2010). Empty runs represent a further important step of the process (Wolfsmayr and Rauch, 2014), as well as the return of fermented digestate to fields in the case of manure. Previous literature demonstrated that biomass transport is primarily impacted by the mass and volume of the feedstock (Laitila et al., 2016; Searcy et al., 2007), the distance (Laitila et al., 2016), travel, loading, and unloading time (Kuptz et al., 2015; Rentizelas et al., 2009) and the transport mode (Hamelinck et al., 2005; Ko et al., 2018; Laitila et al., 2016). Transport analyses have been conducted in several countries using different approaches and show that the cost of woodchips approximate 1.5€ per tonne of dry mass (DM) in Finland for a distance of 10 km (Laitila et al., 2016), or up to 60 USD/t_{DM} for distance over 100 km in the USA (Searcy et al., 2007). By assessing the profitability of manure separation technologies, Meier et al. (2017) suggest a transport cost of the solid fraction of slurry between 31 and 136 Swiss francs (CHF) per tonne DM. In an Irish study (Pöschl et al., 2010), the maximum distances before the energy balance (considering final energy output) of cattle manure transport turns negative appears to be 22 km using agricultural vehicles. Finally, the CO_2 savings of 50% can be achieved in Italy when the manure transport radius remains below 70 km (Capponi et al., 2012).

1.2 Purpose of the project

To reduce GHG emissions by over 50% by 2035, the Swiss Energy strategy envisions the contribution of wood for electricity to double and the one of biogas to triple (SFOE, 2013). Due to high technology and production costs, the use of biomass, and other new renewable technologies, is currently subsidized. To estimate the contribution of these resources in tomorrow's energy landscape and determine the value of governmental support requires a deeper understanding of their logistics chains, of which transport represents a non-negligible share. Unfortunately, recent international studies on biomass transport for energy are scarce (Ko et al., 2018) and inexistent in Switzerland.

In Switzerland, for a biogas plant to be considered "agricultural" and hence receive additional governmental subventions, the maximum transport distance between feedstock production and energy conversion site must not exceed 15 km (FOEN and FOAG, 2016). It is however unknown whether this maximum distance is in line with praxis nor if it corresponds to economic, energetic and ecological efficiency. Similar guidelines do not exist for forest wood although they should be of primary concern when aspiring to an increase of its use for energy. Therefore, the purpose of this study is to address this knowledge gap by providing a comprehensive analysis of the most important forest wood and manure transport chains.

1.3 Objectives

Currently undocumented, an analysis of the prevailing practices in forest wood and manure transport for energy will provide in-depth comprehension of the most and least performant transport chains. More specifically, this study has four objectives:

1) To identify the most important transport chains of forest wood and manure for energy in Switzerland and their frequency
2) To develop a model to calculate the cost, energy inputs and CO_2 emissions from forest wood and manure transport for energy
3) To determine threshold transport distances for the analysed feedstock in regard to costs, energy, and CO_2 emissions
4) To upscale the previous result at the national level and illustrate the current performance of the Swiss cantons regarding forest wood and manure transport

2 Procedures and methodology

The different steps we underwent for this analysis are summarized in the next section. Additional details concerning the procedures and methodology can be found in Schnorf et. al (2020, under review).

2.1 Interviews

In order to understand what are the most important transport chains, we used mental model interviews. Mental models interviews aim at grasping the interviewee's perception without imposing the interviewer's beliefs and capture the plurality of their views (Elsawah et al., 2015; Jones et al., 2011; Morgan et al., 2002). They are useful when structured data on a topic is scarce and when the overall understanding of a system differs with perspectives of interviewees, as it is the case for biomass transport chains (Jones et al., 2011). Preliminary discussions with the sector's key experts were conducted in order to determine the interview candidates for the manure and the forest energy wood sectors. We selected a panel of seven candidates on the topic of forest wood, composed of different types of exploitations (private and public) as well as institutions. We proceeded similarly for animal manure, where four experts including private enterprises and institutions were chosen. The interviews took place in Summer 2019. They were semi-structured and lasted approximately one hour. During the interview, the experts were asked to sketch two or more firewood and woodchips transport chains which they considered most important in Switzerland. Their answers included information on the types of vehicles, the haulage capacity, the final delivery products and volumes, the expected travel distance on trips and empty runs, the service provider and the estimated frequency of occurrence.

2.2 Transport chains evaluations

2.2.1 General approach

The entire transport process encompasses loading/unloading the feedstock, and all the different trips and empty runs that take place between the origin of the biomass to the end-user's location. It includes an additional preparation step for woodchips and the digestate transport to fields in the case of manure. The costs and energy inputs of the entire transport process are directly linked to the time it requires and the distance. Direct CO_2 emissions were estimated according to the fuel consumption and therefore, relate to the energy inputs. Input data for modelling time (9Appendix A.), costs and energy inputs (Table 1) to deliver the biomass from the stand to the final destination were based on data from literature and confirmed by field trips to different Swiss installations. We considered only the direct costs, the machine's hourly fix and variable costs, including fuel costs, and the worker's salaries. Driving time and fuel consumption were estimated according to the main road types (forest, urban and national roads), driving velocities and distances. The distance on forest roads and urban roads were assumed to be 50% of the total trip distance or maximum 3 km, the remaining distance is travelled on national roads. The energy input while driving was derived from the vehicle fuel consumption (Table 1) and the fuel's energy content. According to the national vehicle fleet, all heavy vehicles use diesel, and most cars run on petrol (FSO, 2019). Loading and unloading processes were assumed to use 75% of the optimal driving consumption for trucks, and 100% for tractors.

Table 1: Input values for salaries, vehicle costs, fuel consumption, and permissible load

	Used in transport chains	**Permissible load [t]**	**Load volume [m³]**	**Costs[a,b] [CHF/h]**	**Driving velocity[c] [km/h]**	**Fuel consumption[c] [L/km]**
Salaries						
Enterprise	*FW-P_H, FW-P_L,*	-	-	75.00	-	-
Agriculture	*FW-F, LM-F, SM-F*	-	-	30.00	-	-
SSWB[d]	*FW-SSWB*			0.00		
Machinery					-	-
Round wood Truck	*FW-P_H,C-WSS*	12	15	168.50/134.80	15/35/75	0.52/0.35/0.30
Container Truck 26t	*C-P_L, SM-P*	22	22/40	173/138.40	15/35/75	0.52/0.35/0.30
Semi-trailer Truck 40t (wood)	*C-P_H*	27	90	181.65/145.35	15/35/75	0.61/0.40/0.35
Semi-trailer Truck 40t (slurry)	*LM-P*	27	27	154.55/123.65	15/35/75	0.61/0.40/0.35
Tractor (90-104 kV)	*FW-P_L, FW-F, C-F, LM-F, SM-F*	-	-	55.00	15/25/35	1.20/0.48/0.34
Trailer	*FW-P_L, FW-F, C-F, SM-F*	20	25	50.00	-	-
Slurry tank	*LM-F*	10	10	56.00	-	-
Front loader	*FW-P_H,FW-P_L,SM-F*	-	-	12.50	-	-
Piston pump	*C-I*	-	45 m³/h	13.25	-	20 kV
Pipe	*C-I*	-	-	0.47 CHF/m³	-	-
Car (petrol) [CHF/km]	*FW-P_H,FW-SSWB*	-	-	1.05	35/45/75	0.07/0.06/0.05

[a] Agricultural machinery costs issued from official governmental publications (EAER, 2018). Costs of trucks are retrieved from professional's prize list and include the driver's cost (-10/20% profit margin).
[b] Costs while driving/loading & unloading. The charges are higher when driving because of the heavy vehicle tax applying per km.
[c] Driving velocity and fuel consumption differs according of the road types. We distinguish forest/urban/national roads. Hourly fuel consumption derived from optimal consumption rate.
[d] Small-scale wood buyers.

2.2.2 Performance indicators

In order to estimate the efficiency of the process in terms of costs, energy and CO_2 emissions, and to approximate threshold transport distances we defined following performance indicators.

Economic indicator

To evaluate the cost economic performance of transport, we used the ratio of the income (Table 2) provided by the resource to the cost inherent to transport (CHF/tDM). Most precedent literature has compared the cost of transport to the final cost of production (Gonzales et al., 2013), but considering the incomes from the sales by energy produced allows to estimate the economic profitability of the process when other production costs are unknown. It was calculated as follows:

$$R_C = \frac{I_b}{C_l + C_u + C_p + C_t} \quad \text{(Eq. 1)}$$

In which R_C is our economic performance ratio; I_b is the income from the transported biomass in Swiss francs (CHF) per tonne DM (t_{DM}); C_l, the costs of loading the feedstock (CHF/t_{DM}); C_u, the costs unloading it (CHF/t_{DM}); C_p, the preparation costs (CHF/t_{DM}); Ct the driving costs (CHF/t_{DM}).

Energy indicator

We used the ratio of the primary energy content of the resource to the direct energy used for transport as an indicator for the energy analysis. It was defined as follows:

$$R_E = \frac{PE}{E_l + E_u + E_p + E_t} \quad \text{(Eq. 2)}$$

In which the energetic ratio R_E is obtained with the primary energy (*PE*) of biomass (in MJ/t_{DM}); E_l, represents the energy used by machinery and vehicles to load the feedstock (MJ/t_{DM}); E_u, the energy required while unloading it; E_p the energy used during preparation time, hence the time necessary for the woodchips transporter to be in the right position next to the chipper (MJ/t_{DM}); E_t the energy of fuel consumption to drive the feedstock to final consumers (MJ/t_{DM}).

Table 2: Input values for income, efficiencies, energy content and emissions for the forest wood and manure transport chains evaluation

	Value	Unit
Income		
FW 0.33m [a]	143/167	CHF/Stere
FW 1m [a]	50/66	CHF/Stere
Woodchips per kWh energy produced [a]	0.054	CHF/kWh
Biogas electricity to grid [b]	0.410	CHF/kWh
Biogas plant heat [c]	0.054	CHF/kWh
Efficiencies		
Efficiency firewood (η_w) [d]	63	%
Efficiency woodchips (η_w) [d]	87	%
Electrical efficiency biogas plant (η_{el}) [e]	39	%
Thermal efficiency biogas plant (η_{th}) [e]	17	%
Energy content		
Mass coniferous wood [f]	0.379	t/m3
Energy density coniferous wood [f]	5200	kWh/t
Mass broadleaf wood [f]	0.558	t/m3
Energy density broadleaf wood [f]	5000	kWh/t
Diesel energy content	10	kWh/L
Petrol energy content	9.2	kWh/L
Fuels CO_2 emissions [g]		
Petrol emissions	2320	g CO_2/L
Diesel emissions	2620	g CO_2/L
Avoided emissions from energy [h]		
Fossil part of Swiss district heating mix	208.1	g CO_2/kWh
Imported electricity	345.0	g CO_2/kWh

[a] Price of one stere coniferous / broadleaves firewood and per kWh energy produced for woodchips (WaldSchweiz, 2017).
[b] We assumed the heat sold by biogas plants to be at the same price than the income from woodchips.
[c] Corresponds to the feed-in tariffs paid-out to biogas plants in 2017 (SFOE, 2017).
[d] With an electrical efficiency of 7% for chips (Stettler et al., 2019).
[e] Values measured by the association of agricultural biogas plants (Bolli and Anspach, 2015).
[f] (Hahn et al., 2014)
[g] CO_2 emitted when burning one litre of fuel
[h] (Alig et al., 2017; Messmer and Frischknecht, 2016)

Environmental indicator

For our environmental performance indicator, we first estimate the CO_2 emissions of a reference case, in which the potential final bioenergy produced would be provided by traditional (fossil) energy sources. We assumed that the generated heat substitutes the fossil part of the Swiss district heating mix and that electricity reduces the need for non-renewable power imports. We then compare it to the additional emissions from fuel combustion occurring during the entire transport process of the biomass (Capponi et al., 2012). The formulas we used slightly differ for forest wood (Eq. 3a) and for manure (Eq. 3b) and are defined as follows:

$$R_{CO2} = \frac{AG_{el} + AG_{th}}{G_l + G_u + G_p + G_t} \qquad \text{(Eq. 3a)}$$

Where R_{CO2} is the CO_2 performance ratio, AG_{el} are the avoided emissions from imported electrical energy in kg CO_2/t_{DM} ; AG_{th}, represents the avoided emissions from the fossil part of the Swiss district heating (kg CO_2/t_{DM}); G_l, G_u, G_p and G_t are the emissions generated from loading, unloading, preparing and transporting the feedstock (kg CO_2/t_{DM}).

In the reference case of manure, the feedstock is not brought to a biogas plant, which results in emissions of methane from manure management (MM). These emissions are reduced when bringing the manure to a biogas plant, as the storage time is shorter. Nevertheless, following the method proposed by the Swiss government to evaluated the biogas plant's emissions, additional methane losses occur at the biogas plant during the fermentation of the feedstock and storage of the digestate (FOEN, 2019). Therefore, our environmental indicator for manure was calculated as follows:

$$R_{CO2} = \frac{AG_{el} + AG_{th} + AG_{mm}}{G_l + G_u + G_p + G_t + G_{mm} + G_s + G_f} \qquad \text{(Eq. 3b)}$$

Where R_{CO2} is the CO_2 ratio, AG_{el} are the avoided emissions from imported electrical energy in kg CO_2/t_{DM} ; AG_{th}, represents the avoided emissions from the fossil part of the Swiss district heating (kg CO_2/t_{DM}); AG_{mm} are emissions (CH_4 and N_2O) from traditional MM practices (kg eq-CO_2/t_{DM}); G_{mm} are emissions from MM when the feedstock is brought to a biogas plant (which are lower than AG_{mm} due to e.g. shorter storage time (IPCC, 2019)) (kg eq-CO_2/t_{DM}); G_f are methane losses occurring during AD (kg eq-CO_2/t_{DM}); G_s the emissions from digestate storage (kg eq-CO_2/t_{DM}).

2.2.3 Evaluation data forest wood

The entire transport process includes different runs to the consumers and back, loading/unloading the feedstock and, in the case of woodchips, the preparation (and waiting) time of the vehicle at the loading location. This step was shown to be relevant for woodchips, in particular for semi-trailer trucks, which can require significant amounts of time before being set in the correct position and starting to be loaded (Kuptz et al., 2015). The cost or energy input of the wood chipper were not considered in this analysis, as it rather belongs to the production process than to transport itself. However, the loading time and the associated cost of the transport trucks, is affected by the efficiency of the chipper, which requires more or less time according to the machinery used. We assumed the professionals to use a Jenz Hem chipper (max output 155 bcm/h) and farmers the Musmax Wood terminator (max output 115 bcm/h) (Lemm et al., 2018a). The average output was determined by a 50% share of round energy wood and 50% waste wood as chipping waste wood reduces the maximum output by 35% (Lemm et al., 2018a). The distances travelled by forest wood were estimated by the experts, whereby minimal and maximal values were used.

When analysing forest wood, we differentiated between coniferous (spruce, larch, or fir) and broadleaves (beech, maple, or ash)[1]. The higher mass of broadleaves affects the transport process in terms of carried volume, but also the unit conversion into tonne of dry mass (t_{DM}). Consequently, the higher mass of broadleaves wood leads to higher energy yields and therefore, price. The price, and potential income, of firewood is per stere, whereas it is per kWh of energy for woodchips. The CO_2 emissions of the use of firewood or woodchips are considered neutral and possible nitrogen emissions during combustion are negligible (Messmer and Frischknecht, 2016). Finally, their emission reduction potential from a substitute heat or electricity source is affected by the efficiency of wood heating installations. Input values used in the model are depicted in Table 2.

2.2.4 Evaluation data manure

To complement the interviews, additional information could be retrieved from the HODUFLU dataset provided by the Swiss federal office for agriculture (FOAG, 2018). HODUFLU is a program that records all manure exchange flows between farms or third parties. It was initially created to regulate the nutrient flows and contains information about municipality of origin and destination, manure type, dilution rate, volume, and Nitrogen content. In 2016, 10% of the total manure produced in Switzerland was exchanged using HODUFLU, of which 20% was going through a biogas plant (FOAG, 2016). Biogas plants in the dataset were recognisable thanks to publically available information. Knowing the municipality of manure origin, distances between suppliers and receivers could be approached conducting an Origin-Destination-Cost-Matrix on the Network Analyst extension of ArcGIS 10.6. Following this, a distance of 5 km was used for liquid manure transport, 9 km for solid manure and 7 km for digestate.

Manure transport encompasses loading and unloading the feedstock, includes all empty runs, and the transport of digestate to the field. We performed the analysis on the initially transported Dry Matter (DM), which varies according to the feedstock type (solid or liquid). We took into account the dilution of slurry and assumed a mass of solid manure of 750 kg/m^3. Calculations on our dataset (FOAG, 2018) indicate that diluted slurry has an average DM content of 4.5%, while it is of 32% for solid manure (SM). The dataset also shows, that after the fermentation, digestate has a DM content of 8%, which was confirmed by sector experts. Because of the different DM content of manure and digestate, we defined a compensation factor for liquid or solid manure, which additionally considers the substrate reduction occurring during fermentation (see Schnorf et al., 2020, supplementary information).

The biogas yields and subsequent methane outputs are based on the organic fraction (oDM) contained in the animal excretions (Table 3). The potential income of manure reflects the final energy output and depends on types, categories (Table 3), and conversion efficiency The final energy output was estimated using methane yield values from the KTBL (2013), as they consider the CH_4 reduction occurring directly

[1] The main part of this report will show the results for broadleaves wood, as it is more frequently used for energy purposes than coniferous wood. Additional results for coniferous woods can be found in the appendix. Results for coniferous wood are 20% to 40% lower.

after excretion (Burg et al., 2018). The produced electricity is subsidized to an amount of 0.41 CHF/kWh (SFOE, 2019b). Farmer's rarely sell their heat but rather use it in their personal house or in the stables. Therefore, the heat price of the district heating represents the avoided costs of purchased energy. For the energy performance ratio, the primary energy of each feedstock depends on its calorific value, which varies according to the animal and the amount of DM.

We estimated the CH_4 and N_2O emissions from manure management using the methods and maximum methane producing capacity described in the 2006 IPCC Guidelines (IPCC, 2019). We consider the suggested maximum methane producing capacity, as well as system-specific methane conversion factor (MCFs) for the cool climate of Switzerland and N_2O emissions factors. They were converted into CO_2-eq using a GWP of 25 for CH_4, and 298 for N_2O (FOEN, 2020). The potential income, primary energy, and emissions (kg eq-CO_2) savings were calculated for each manure type directly on the HODUFLU dataset, and therefore, provide precise average values per tonne of solid and liquid feedstock in Switzerland.

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Table 3: Specificities of manure category and type: DM, oDM, Lower heating value (LHV), biogas and methane yields, emission factors

Animal	Category	Type	**DM**[a] [kg/t]	**oDM**[a] [kg/t]	**LHV**[b] [MJ/kg DM]	$Y_{BG(A)}$[b] [m^3 CH_4/kgVS]	P_{CH4}[b] [%]	$Y_{CH4(A)}$[c]	$MCF_{(A)}$[c]	N_2O[c]
Calf	Calf SM	Solid	200	150	15.5	0.450	55%	0.18	2.00%	0.50%
Cattle	Slurry (dairy)	Liquid	90	70	16.3	0.280	55%	0.24	13.50%	0.20%
	Excrement poor slurry (dairy)	Liquid	75	40	16.3	0.280	55%	0.18	13.50%	0.20%
	Slurry (fattening)	Liquid	90	65	15.2	0.280	55%	0.18	13.50%	0.20%
	Pile SM (dairy)	Solid	190	150	17.5	0.450	55%	0.18	2.00%	0.50%
	Stable SM (dairy)	Solid	210	175	17.5	0.450	55%	0.18	2.00%	0.50%
	Stable SM (beef)	Solid	210	155	15.5	0.450	55%	0.18	2.00%	0.50%
	Slurry from separation [d]	Liquid	40	28.8	16.3	0.280	55%	0.18	13.50%	0.20%
	SM from Separation [d]	Solid	200	164	17.5	0.370	55%	0.18	2.00%	0.20%
Goat/Sheep	Sheep/goat SM	Solid	270	200	15.6	0.450	55%	0.19	10.00%	1.00%
Horse	Horse SM	Solid	350	270	18	0.420	60%	0.33	2.00%	0.50%
Mixed	Slurry (mixed)	Liquid	66	44	15.7	0.340	58%	0.33	13.50%	0.20%
Poultry	Hen SM (belt)	Solid	350	250	15	0.500	65%	0.39	1.50%	1.00%
	Hen SM (layer)	Solid	500	330	13.9	0.500	58%	0.39	1.50%	1.00%
	Hen SM (young)	Solid	500	430	13.9	0.500	58%	0.39	1.50%	1.00%
	Poultry SM (fattening)	Solid	650	440	13.9	0.500	58%	0.36	1.50%	1.00%
	Turkey SM	Solid	600	400	14	0.500	58%	0.36	1.50%	1.00%
Swine	Slurry (fattening)	Liquid	50	36	15.1	0.400	60%	0.45	13.50%	0.20%
	Slurry (breeding)	Liquid	50	33	13.9	0.400	60%	0.45	13.50%	0.20%
	Swine SM	Solid	230	189	15.1	0.400	60%	0.45	2.00%	0.50%

note: SM = Solid Manure, [a] GRUDAF, 2009, [b] KTBL 2013 [c] IPCC, 2019 , [d] Meier et al., 2017
$Y_{BG(A)}$ = Biogas yield per animal category A [m^3 CH_4/kgVS]
$Y_{CH4(A)}$ = Max. CH_4 production potential IPCC

2.3 Maximum transport distances

The above-mentioned indicators further allowed to estimate the maximum transport distance of the different feedstock without consideration of the remaining production costs, energy inputs or emissions. These values give an indication of how far a transporter can go before the haulage becomes unprofitable, and more generally before the transport inputs exceeds the potential outputs of using the resource. Calculated with increasing distance, they also allow to compare the transport chains on equal scope. The break-even point is reached when the value of the ratios is below one.

2.4 Cantonal upscaling

2.4.1 Upscaling forest wood

To estimate the cantonal performance of forest wood transport we combined the Swiss forestry statistics with a GIS analysis using maps of the forest mix (FSO, 2013) and digital height models (Swisstopo, 2019). First, we conducted a GIS analysis (ArcGIS 10.6) to estimate both the share of each wood type (broadleaves and coniferous) and the amount of wood necessitating intermediate winter safe storage (C-WSS) for each canton (see Schnorf et. al (2020), supplementary information). Then, we added this information to the forestry statistics, which record the cantonal firewood and woodchips harvest (m^3). The frequencies of occurrence estimated by the experts of each firewood or woodchips transport chains were averaged by category (FW and C) and rescaled to 100%. For each canton, the total costs, energy inputs and CO_2 emissions generated by all transport chains are summed and compared to the total potential income, primary energy and avoided emissions. For instance, the transport chain C-P_H was calculated as follows:

$$Cantonal\ Cost_{C-PH} = P_C * (1 - WSS_C) * WT_{C,T} * M_T * TotCost_{C-PH} + P_C * (WSS_C) * WT_{C,T} * M_T * TotCost_{C-WSS} \quad \text{(Eq.4)}$$

Where: *Cantonal Cost$_{C-PH}$* is the total cost in the canton of the wood transported following the chain C-P_H in CHF; P_C is the total woodchips production in canton *C* in m^3; WSS_C is the share of forest requiring additional winter safe storage in canton *C* in %; $WT_{C,T}$ is the share of each wood type *T* in canton *C* (broadleaves or coniferous wood) in %; M_T is the dry mass of the different wood type *T* in kg/m^3; $TotCost_{C-PH}$ is the total cost of transport of the transport chain C-PH in CHF/t_{DM}; $TotCost_{C-WSS}$ is the total cost of transport chain C-WSS in CHF/t_{DM}.

The potential income, primary energy, and avoided emissions (through final energy conversion) were obtained from the total harvested forest wood quantities. Following this, the total potential income of woodchips could be estimated with Eq. 5.

$$Cantonal\ Income_C = P_C * WT_{C,T} * m_T * E_T * \eta * I_C \quad \text{(Eq.5)}$$

Where the *Cantonal Income*$_c$ is the total income generated in the canton by chips in CHF; P_C is the total woodchips production in canton C in m^3; WT_{CT} is the share of broadleaves or coniferous wood in %; m_T is the mass of the wood in kg/m^3; E_T is the energy content of the wood in kWh/t; η is the efficiency of the plant and I_C is the income of chips in CHF/kWh produced.

The final performance of the cantons was then estimated as such:

$$Cantonal\ cost\ performance = \frac{Cantonal\ Income_C + Cantonal\ Income_{FW}}{Cantonal\ Costs\ of\ all\ chains} \quad \text{(Eq.6)}$$

Where the *Cantonal cost performance* is the final economic performance; *Cantonal Income*$_c$ is the total income generated in the canton by chips in CHF; *Cantonal Income*$_{FW}$ is the total income generated in the canton by firewood in CHF; and *Cantonal Costs of all chains* is the sum of the total cost of all transport chains in CHF.

Finally, to provide a range of efficiencies, we calculated all ratios with the shortest distance mentioned by the expert and with the longest one.

2.4.2 Upscaling manure

For the manure part, the interviews led to the definition of criteria (Table 4) that allowed to identify the transport used for each entry of the dataset. As the load volumes of agricultural trailers and professional truck containers are similar, agricultural solid manure transport (SM-F) was defined by road distances below 10 km, the remaining solids being attributed to professionals (SM-P). Information on existing underground slurry pipes between farms and biogas plants was gathered directly at the biogas plants. The plants possessing such infrastructure were identified and used when the distance (direct line) was below 5 km. We defined agricultural slurry transport by distance below 10 km and load volumes up to 25 m^3 and attributed all remaining liquid transport to professional tank trailers.

Table 4: Criteria used in the manure dataset to attribute a chain to each manure exchange flow

Name of transport chain	Manure type	Quantity	Distance	Possesses underground slurry pipes
LM – F	Liquid	< 25 tonnes	< 10 km	–
LM – I	Liquid	all	< 5 km [a]	“yes”
LM – P	Liquid	> 10 tonnes	All	–
SM – F	Solid	all	< 10 km	–
SM – P	Solid	all	> 10 km	–

[a] Straight line distance between the origins and destinations. We deliberately used an average distance of 5 km in discussion with sectorial experts, as it is in between the maximal length of 8.5 km and the other known pipeline lengths.

The frequency of each transport chain was estimated on the dataset by summing the total volumes of manure that had been transported using this procedure. We calculated the costs, energy inputs, and emissions of transport per tonne DM on the inflow (manure) and outflow (digestate) dataset, as well as the potential income, primary energy, and all manure related emissions. All values from inflows and outflows were summarized by canton to provide the economic performance ratio R_C, the energy performance ratio R_E, and R_{CO2} (ratio of the avoided emissions to the emissions linked to the use of biomass for energy) ratios of the cantons.

3 Results and discussion

3.1 Identified transport chains

A total of 12 representative transport chains were identified from the interviews, of which seven refer to forest wood, and five to manure (Figure 1). For each of the different woodchips chain, one supplementary optional transport chain can be added. The transport chains can be distinguished by service providers: professionals (P), agricultural (F) or small-scale wood buyers (SSWB). One manure transport chain is related to the existing slurry pipe infrastructure (I) If not specified differently, the delivered volume is determined by the vehicle’s load volume and permissible payload (Table 1).

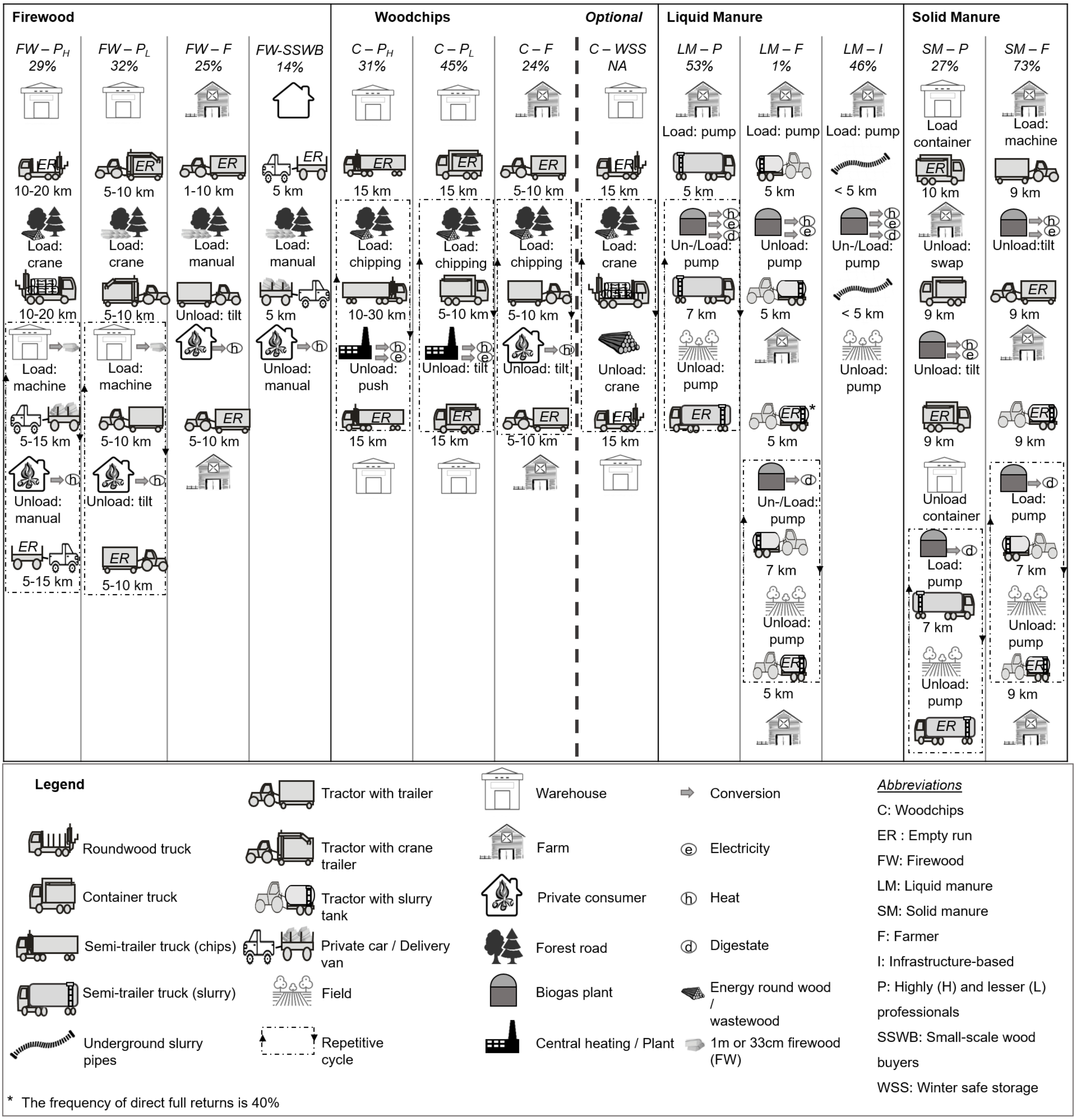

Figure 1: Identified and analysed transport chains of forest wood and manure in Switzerland. The percentage below the transport chain name is the expected frequency,

3.1.1 Forest wood transport chains

During the interviews, we differentiated firewood or woodchips transport chains. The final delivery volume for the three first firewood chains is three steres (coinciding with the average firewood consumption per installation (Stettler and Betbèze, 2019)) and one stere for small-scale wood buyers (FW-SSWB). Their water content is 35% as the timber remains to dry in the forest for up to two years before transformation. The firewood is expected to reach its optimal water content (15%) at the consumer's place before burning. In the firewood chain most frequently described (FW-P_H), the energy round wood is first brought to the enterprise's warehouse in large quantities for further transformation into 0.33 m logs and delivered to the final consumer with a delivery vehicle. It can be attributed to a highly professionalized forestry enterprise specialized in the production of energy wood, and its average frequency was estimated at 29%. The second firewood chain (FW-P_L) differs from the previous one, in that the chosen transport mode is the tractor, and the feedstock is prepared in 1-metre bundles at the forest road, maintaining the first load volume to constant 20 stere (14.2 m^3). This transport chain, representing up to 32% of all firewood, is mostly used by the forest districts, as their diversified activity requires multifunctional machinery. Another firewood provider in Switzerland is the farmer, who provides this services for additional income during the calmer winter months. In this agricultural chain (FW-F), the wood is processed into 0.33 meter logs and loaded manually in the trailer directly at the forest road before delivery to the end-consumer by tractor. As the most common procedure in some regions, this transport chain can be expected to be used by 25% of all firewood transporter. Finally, individuals can buy the wood in the forest and prepare the wood logs themselves, before transporting it with private cars and trailers (FW-SSWB). All distances to the final consumer were estimated between 1 and 20 km (Figure 1 and Table 5).

In the three first woodchips transport chains (C-P_H, C-P_L, C-F*)*, green chips (50% water content) are delivered to consumers at different transport distances and using distinctive transport modes. Consumers can be small or medium-sized communal heating to large CHPs. Again, we differentiate between two professionals (C-P_H) that operates with semi-trailers (90 m^3) and C-P_L using a container truck (40 m^3); and the agricultural chain (C-F) where a tractor and a trailer (25 m^3) is used. Because of the important bulk volume of chips (we used a conversion factor of 2.8 bulk cubic meters chips for 1 m^3 wood), the permissible load weight of the trucks is rarely attained with 25 m^3 or 40 m^3 containers. Therefore, the use of semi-trailer trucks equipped with walking floors increased these last years. Woodchips transport is mostly combined with the chipping process, but the costs and energy inputs of the chipper are not considered in this analysis. However, the time required for chipping represents the loading time of the different transport vehicles. For time and cost optimisation, chipping and transport occurs on a full day of work (8.5 hours in Switzerland) with several vehicles. The haulage trucks drive empty to the forest location, get prepared next to the chipper for loading, and drive back and forth from the forest location to the consumers in a repetitive cycle. The agricultural trailer and the container truck unload their carriage by tilting the container, while the semi-trailer uses a walking floor that pushes the chips in the end-location bunker. The transport distances estimated by the experts are situated between 5 and 30 km (Table 5). The most frequently used chain is the lower professional (C-P_L) as its use makes up approximately 45% of all woodchips transport. It is followed by the highly professional (C-P_H) with 31% and the farmer (C-F) with 29%. The last woodchips chain (C-WSS) is additional to the above-mentioned, as it takes place in mountainous areas to secure sufficient provision during winter when demand is highest and locations hardly accessible. It consists in transporting the energy round wood to an accessible storage location situated up to 5 km further than the initial forest road, from where the three precedents transport chains take place. According to interviewees, the amount required for ensuring the wood fuel provision during winter can be as high as 10% of the woodchips supply below 600m altitude, 25% between 600 and 800m, and 50% above 800m altitude. This must, however, be considered a relatively conservative supposition.

Table 5: Distances used in calculations.

Name of transport chain	**Distance 1/ Distance 2 [km]**	**Transport chain type**	**Transport chain name**	**Distance 1/ Distance 2 [km]**	**Chain type**
FW - P_H	10/5	short	C - P_H	25/10	short
FW - P_H	20/15	long	C - P_H	25/30	long
FW - P_L	5/5	short	C - F	5/5	short
FW - P_L	10/10	long	C - F	10/10	long
FW - F	1/5	short	C - WSS	15/5	-
FW - F	10/10	long	LM - P	5/7	-
FW - SSWB	5	short	LM - F	5/7	-
FW - SSWB	5	long	SM - P	9/7	-
C - P_L	15/5	short	SM - F	9/7	
C - P_L	15/10	long			

3.1.2 Manure transport chains

Animal manure can be both liquid (LM) or solid (SM) and, therefore, its transport requires different types of trailers. However, digestate is going back to fields in liquid form only[2]. The digestate outflow service provider is assumed to coincide with the manure provider, hence, SM carried to the plant by professionals will return to fields with the professional liquid means of transport.

Professional slurry transport (LM-P) is the most direct transport chain, due to a load capacity of 27 m^3 and because it avoids all empty runs by optimizing the route. Therefore, it is frequently used (53%). Farmers bring slurry (LM-F) to biogas plants with tractor and tank trailers and we assumed that digestate was directly brought to fields in 40% of the cases only. This high share of empty returns is due to several reasons: first, fields fertilization mainly occurs in spring and summer when animals spend most time

[2] In our dataset, the share of solid digestate was negligible and was, therefore, not considered for the actual transport chains calculations, but it was in the dataset calculations (upscaling).

outdoors and when the manure is not collected. Second, a major motivator to deliver manure to biogas plants is the lack of storage space. Applying the criteria described in section 2.4 on our dataset allows to suggest that this options is rarely used, as it represents less than 1% of all liquid manure transport. Finally, where the infrastructure allows it (46% of liquid manure), the slurry can be pumped directly to the fermenter of the plant by means of underground pipelines and piston pumps (LM-I). The length of these pipes usually ranges from a few hundred meters to 4.5 km, with the longest being 8.5 km.

To transport SM, professionals (SM-P) commonly use a container truck (22 m^3), which they exchange with a full container at the manure incurring location before bringing and unloading it to the plant. Agricultural SM transport (SM-F) is effectuated with tractors and trailers and cannot avoid an empty run between the farm and the biogas plant due to the liquid digestate. Consequently, one additional empty run between farm and biogas plant is necessary before transporting the digestate with the corresponding 10 m^3 slurry tank to the field. As distances rarely exceed 10 km, agricultural transport represents 76% of all solid manure transport.

All experts agreed that agricultural transport does not exceed 10 km, but as mentioned above, the Origin-Destination cost matrix analysis undertaken revealed that slurry is on average carried on distances of 5 km, SM on 9 km, and digestate on 7 km.

3.2 Transport economic performance

3.2.1 Forest wood transport costs

Following results and Figure 2 (top) depict the costs of broadleaves wood and manure in t_{DM}. Additional results for coniferous wood are presented in the Appendix C. The entire process of transporting firewood costs between 27 CHF/ t_{DM} and 232 CHF/t_{DM}, for the small-scale wood buyer (FW-SSWB) and the farmer (FW-F) respectively. This large difference is due to the fact that the only costs private individual encounters in our calculations is the cost of the vehicle itself. This results in an economic performance ratio (R_C) of 11.6 : 1, which shows that the potential value generated by the wood would be 12 times higher than what it costs to transport it. However, the steep curve of its ratio (fig. 2 bottom) suggests that this only applies to short distances and that it becomes less performant than the higher professional FW-P_H after 11 km only. The latter can keep its costs below 100 CHF/T_{DM} even when assuming maximum distances, which leads to a performance indicator of 4.3 : 1 (Figure 2 (top)) also shows that transport itself is not the only costly part of the process. For instance, the manual loading process of firewood can affect prices significantly and impact costs more than transport itself. This is particularly visible in the agricultural firewood chain (FW-F), in which the effects of the lower salaries are wiped out by the time necessary to manually load and unload the feedstock, and the associated non-negligible machinery costs (the tractor and the trailer themselves cost 105 CHF/h, Table 1).

All woodchips transport (C-P_H, C-P_L, C-F) costs fluctuate between 23 CHF/ t_{DM} and 39 CHF/ t_{DM} but additional charges of up to 23 CHF/ t_{DM} apply if additional intermediate winter storage (C-WSS) takes place. With a R_C of 8.6 : 1 on short distances to the final consumer (5 km), the less professional chips transport chain (C-P_L) is the most efficient one on fixed distances (Table 5), followed closely by C-P_H (8.4 : 1) driving 10 km. However, this tendency is reversed for coniferous woods, for which C-P_H is slightly more efficient than C-P_L, due to the more important transported coniferous wood volumes. In fact, with a water content of 50%, 90 m^3 semi-trailers can only be filled with the equivalent of 68 bulk m^3 of broadleaves woodchips. A 15% reduction of the water content allows an augmentation of this load volume to 88 bulk m^3 broadleaves chips and increases the R_C ratio of this chain by 25%. The optional winter safe storage would reduce the performance of the chains by 38% on average. Due to their higher mass, coniferous wood costs 23% to 47% more than broadleaves wood and lead to lesser income. This significant difference points out the importance of wood types used for energy production.

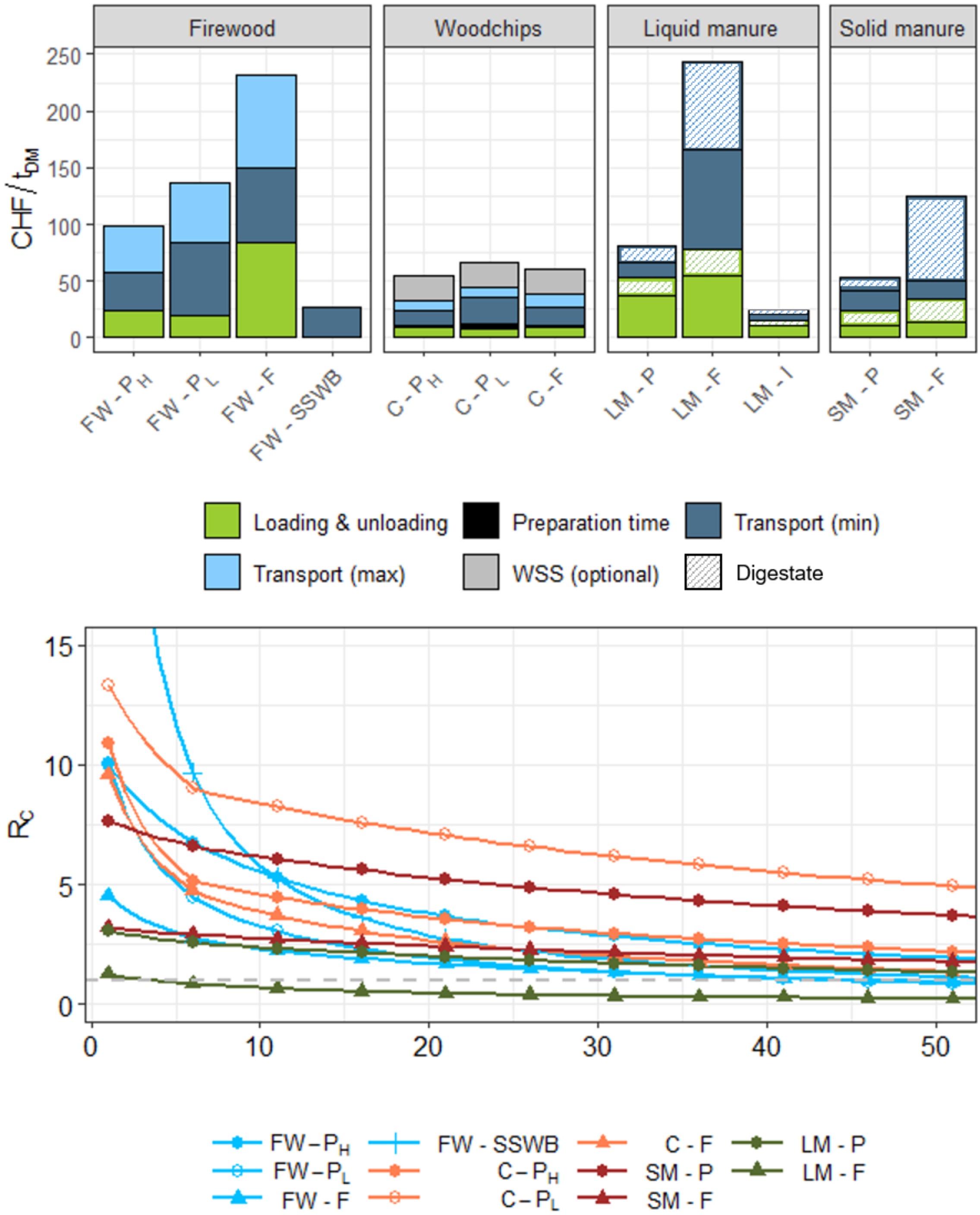

Figure 2: Costs of (broadleaves) wood and manure transport on distances (top) and the R_C income-cost ratio with increasing distance to end-consumer. The grey dashed line at one represents the distance after which the potential costs exceed the potential income (bottom)

3.2.2 Manure transport costs

The cost of transporting manures varies between 24 CHF/DM for underground slurry pipes (LM-I) and 244 CHF/t_{DM} for agricultural slurry tanks with (LM-F). However, most plants benefitted from existing pipes built by precedent farmers, and the costs we estimated[1] are not easily traceable. Building new slurry pipes today can be expected to be more expensive and complicated due to the built-up infrastructure (it is more expensive to dig through asphalt/concrete) or restrictions (water protection). The larger haulage capacity (27 m^3) and the numerous empty runs avoided by optimizing their trips of the professional slurry transporters (LM-P), lead to costs of 82 CHF/t_{DM}. Overall, solid manure transport is less expensive than liquid manure due to its larger amounts of dry matter (4.5% DM in slurry and 32% in solid manure). It also performs better as it leads to higher methane yield and, therefore, higher income. Calculated on the dataset, a potential income of 210 CHF/t_{DM} can be expected for slurry, whereas it is of 327 CHF/t_{DM} for SM. This leads to a R_C of slurry of 2.1 : 1 for professionals, 0.9 : 1 for agricultural transport and 8.9 : 1 for underground pipe transport, and suggests that using 10 m^3 slurry tanks is not profitable even on distances of 5 km. Similarly, professional SM transport (SM-P) also performs better than the agricultural one (SM-F) with R_C of 6.1 : 1 and 2.6 : 1.

Digestate loading and transport on 7 km cost nearly as much as slurry and is even more significant than solid manure transport (Figure 2, top). However, it is arguable whether it must be considered in the analysis, since undigested manure also serves as a fertilizer and would be driven to fields anyways. Not considering the return of digestate to fields in the analysis reduces slurry transport costs by 59-70% (or LM-P to 50 CHF/t_{DM}, LM-F to 143 CHF/t_{DM} LM-I to 17 CHF/t_{DM}) but the most notable difference occurs for SM-F, where a reduction of 75% of the previously estimated costs can be observed, resulting in 25 CHF/t_{DM}. This is explained by the high compensation factor, as the amount of digestate corresponding to a solid manure truck takes into account the difference in dry matter and in vehicle's load volume.

3.3 Energy performance

3.3.1 Forest wood energy performance

The energy indicator R_E depicts the relation of the primary energy contained in the feedstock to the direct energy deployed for its transport. The energy inputs used for transporting broadleaves firewood ranged from 52 MJ/t_{DM} (FW-SSWB) to 511 MJ/t_{DM} (FW-F), while they were situated between 44.7 MJ/t_{DM} (C-P_H) and 121 MJ/t_{DM} (C-F) for woodchips transport chains (Figure 3, top). Figure 3 shows that the energy input of loading/unloading woodchips was nearly inexistent, as vehicles are stationary during this process and that the energy of the chipper was not considered in our analysis (section 2.2.3). Results for coniferous woods can be seen in Appendix D.

Using the fix distances mentioned by the experts in the interviews (Table 5), the highest performance for broadleaves firewood was again achieved by the small-scale firewood buyer (R_E of 320 : 1). However, its steep curve (Figure 3, bottom) also shows that after only 11 km, the highly professional FW-P_H transport chain performs better. After a very short distance, the agricultural firewood transport chain (FW-F) and the lesser professional (FW-P_L) performed very similarly. However, the energy inputs of these least performant transport chains summed up to 1.2% - 3% of the primary energy contained in the resource. The best performance for woodchips transport was obtained by the lesser professionalized (C-P_L) with a R_E of 348 : 1 on short distances and 256 : 1 on long distances. This means that the direct energy of woodchips transport represents no more than 0.4% of the total energy contained in the resource. As semi-trailers usually travel longer distances (C-P_H), they performed slightly worse than the container trucks. However, on equal distances (Figure 3, bottom) they achieve better results. Finally, even though the final consumers of woodchips and firewood are difficult to compare, it is possible to notice that the most professionalised firewood transport (FW-P_H) was more efficient than agricultural chips transport (C-F) after 5 km. This demonstrates that woodchips transport is not always more interesting than firewood and that its production is worth consideration in some situation.

3.3.2 Manure energy performance

The loading/unloading process was significant in manure transport chains. In fact, the energy used by loading/unloading slurry on semi-trailer tanks (LM-P) was more important than transport itself, since the time necessary to drive 5 km is significantly shorter than the time required for loading/unloading. This was not the case for agricultural liquid manure transport (LM-F) in which driving slurry and digestate required the highest amount of energy. The R_E of this least efficient transport chain is of 22 : 1 and, therefore, is still significantly positive. This underlines that it is energetically interesting to transport liquid manure. The only direct energy input for slurry transport through underground pipes was the electricity used for pumping, therefore, this transport chain (LM-I) is the most efficient manure chain. Solid manure transport was less energy demanding than liquid manure. Again, this is attributable to the important amounts of DM (32%), which directly impacts values per tonne of DM. This leads to performance ratios of 71 : 1 for professional transport (SM-P) and 42 : 1 for agricultural transport (SM-F), meaning that the direct energy inputs represent 1.4% or 2.3% of the primary energy contained in the resource.

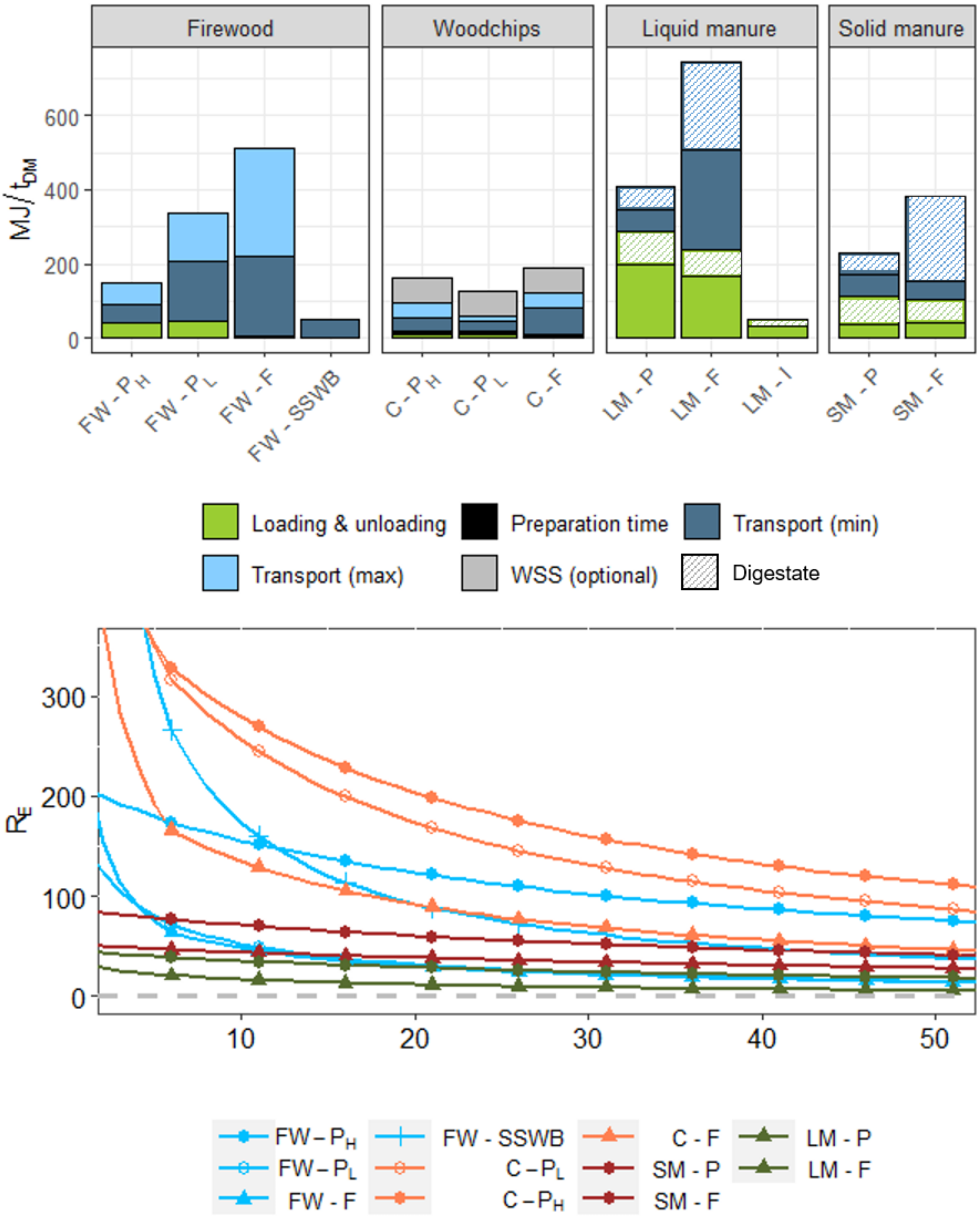

Figure 3: Energy input for the different steps of the transport process of forest wood (broadleaves) and manure (top) and R_E of different forest wood (broadleaves) transport chains with increasing distance to final consumer

3.4 Environmental evaluation

In the environmental ratio R_{CO2}, we compared the direct CO_2 emissions per tonne DM for a reference scenario where no biomass is transformed into energy to the scenario in which it is (Figure 5). For all chains, the R_{CO2} is lower than the R_E ratio, since the avoided emissions depend on the feedstock conversion efficiency at the plant.

3.4.1 Environmental performance forest wood

Forest wood eq-CO_2 were negligible and as only direct emissions from fuel combustion were considered, energy input and CO_2 emissions follow the same trend. The lower conversion efficiency of firewood to woodchips also increased the gap between the R_{CO2} of the two resources. Broadleaves firewood transport chains emitted between 7 kg CO_2/t_{DM} (FW-P_H) and 37 kg CO_2/t_{DM} for (FW-F) following which their R_{CO2} is respectively 90 : 1 and 16 : 1.The environmental performance ratio of small-scale buyers (SSWB) is highest only for the first 15 km, a distance after which it is affected by the smaller hauled volumes (Figure 4, left).

In turn, emissions of chips transport ranged between 3 kg CO_2/t_{DM} and 14 kg CO_2/t_{DM} and resulted in R_{CO2} of 253 : 1 to 93 : 1 for the container woodchips truck and the agricultural trailer respectively. Again, winter safe storage (C-WSS) nearly doubled the direct environmental impact of woodchips transport by adding 4.9 kg CO_2/t_{DM} (broadleaves) and 6.1 kg CO_2/t_{DM} (coniferous) to the initial emissions and reduced their R_{CO2} by 23%.

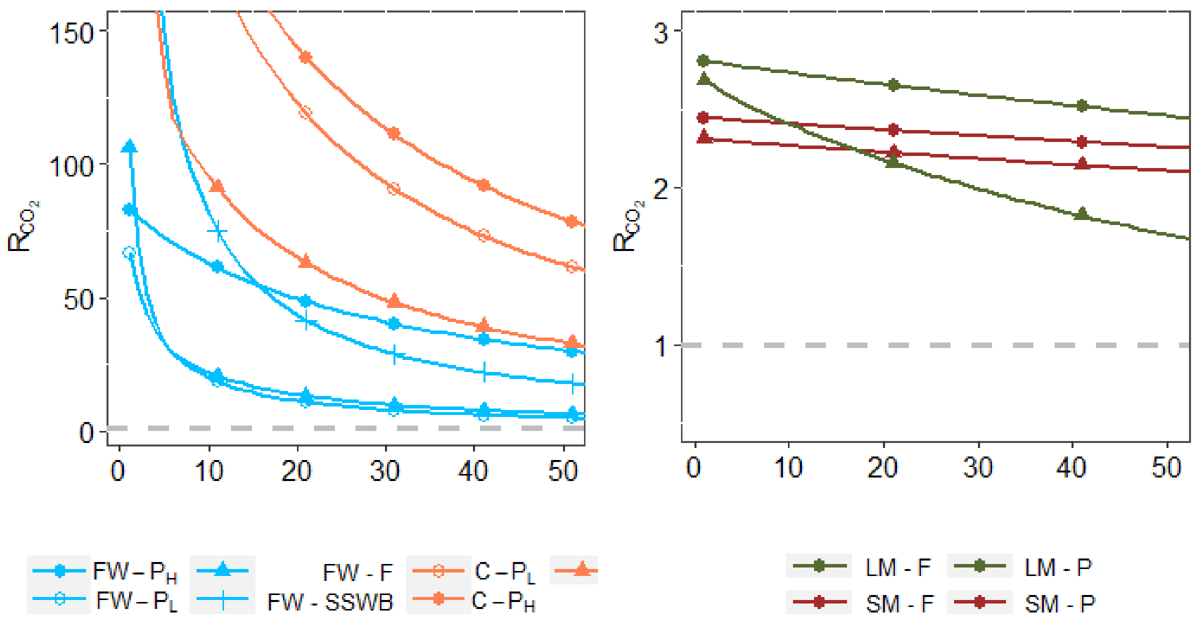

Figure 4: Environmental performance indicator of (broadleaves) forest wood (left) and manure (right) with increasing distance to end consumer.

3.4.2 Environmental performance manure

Manure transport emissions included emissions from manure management (MM) and CH_4 production at the biogas plant which drastically impacted the results of the agricultural feedstock. Transport emissions of animal manure were negligible compared to CH_4 emissions before, during, and after its fermentation (Figure 5). On the basis of the maximum CH_4 output (IPCC, 2019) and available N recorded in the manure dataset, liquid manure would emit 510 kg eq-CO_2/t_{DM} and solid manure 103 kg eq-CO_2/t_{DM} with traditional MM practices. Bringing the animal excretions to biogas plants and reducing manure storage time to 12 days would reduce MM emissions of slurry to 126 kg eq-CO_2/t_{DM} and the ones of SM to zero. However, solid manure produces more CH_4, which led to losses during production (2%) and digestate storage (3%), exceeding traditional MM (163 kg eq-CO_2/t_{DM}). With consideration of the avoided emissions from electricity and heat substitution, the ratio R_{CO2} for professional and agricultural SM transport was of 2.4 : 1 and 2.3 : 1. This means that for 1 kg eq-CO_2 emitted in transport, 2.3 kg are avoided through reduced manure management systems and avoided energy from substitute fossil sources.

The higher avoided MM emissions and lower methane outputs of slurry led liquid manure transport to perform better than solid manure. However, the share transport represented in the total potential emissions of a full truck makes up on average 13%, as most eq-CO_2 was attributable to leakages and storage losses. Therefore, not including digestate transport in our calculations affects the results only marginally and the results must be interpreted cautiously. Direct measurement on Swiss agricultural biogas plants have shown that all leakages (including digestate storage) at the plant represent less than 1% (Ökostrom Schweiz, 2020). This would lead to R_{CO2} ratios of up to 12 : 1 for solid manure and 5 : 1 for slurry, and highlights the environmental benefits of using this resource for energy production.

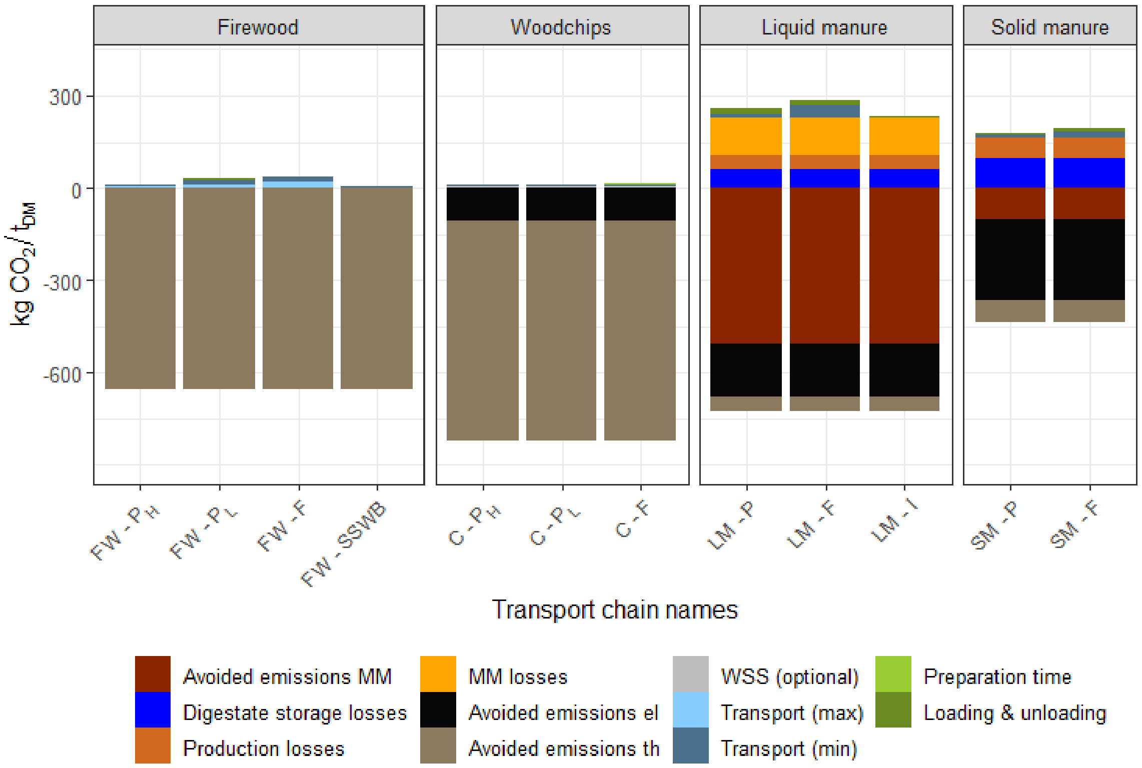

Figure 5: eq-CO2 emissions of forest wood and manure transport compared with avoided emissions from a substitute energy source and methane emissions

In order to estimate the potential of manure transport, we undertook the same analysis of CO_2 saving considering an upgrading of biogas into biomethane. The analysis was conducted assuming a fuel consumption of 4 kg/100 km biomethane, 5.6 L/100 km for a diesel car and 6.2 L/100 km for a petrol cars (CREG, 2018; PTV Planung Transport Verkehr AG, 2009). Emissions from bio-CH_4 are null, since they are completely renewable. The Swiss car fleet is composed of 70% petrol and 30% diesel cars (FSO, 2019). Calculations based on the manure exchange dataset showed that solid manure could produce 140 kg CH_4/t_{DM} and liquid manure 91 kg CH_4/t_{DM}, which resulted in respectively 500 and 321 kg CO_2-eq/t_{DM}. This increased the R_{CO2} ratios as depicted in Table 6 below:

Table 6: Environmental performance ratio R_{CO2} if biogas were upgraded into biomethane for vehicles

Name of transport chain	**R_{CO2}**
LM - F	3 : 1
LM - P	3.2 : 1
LM - I	3.6 : 1
SM - F	3.2 : 1
SM - P	3.4 : 1

3.5 Maximum transport distances

The maximum transport distances of the different feedstock according to our three indicators are shown in Table 7. Our results indicate that the costs were the first barrier to transporting the analysed biomass, as the energy contained exceeds the direct energy input of transporting the resources over hundreds of kilometres. According to their transport costs, firewood could reach destination up to 110 km whereas woodchips could be transported up to 477 km. However, this margin would be expected to be significantly reduced if the remaining production costs were to be integrated in the analysis.

Slurry is the resource that should be used most regionally, with distances remaining below 82 km for the most professional and optimized (hence no empty runs) transport chain (LM-P). The least performant transport chain is the agricultural slurry transport (LM-F), as 3 km should not be exceeded. This also indicates that slurry is the only feedstock that might be carried further than profitable economically, as our dataset reveals average slurry transport distances of 5 km. However, when excluding the transport of digestate from the analysis, maximum transport distances would be increased to 10 km. For solid manure, the distance between farm and plant can be as far as 327 km when using professional modes of transport (SM-P) and 137 km with agricultural trailers (SM-F)

When considering the energy contained in the feedstock, the overall values are much higher than when following the economic evaluation. Even if significant additional energy inputs are to be expected from wood production and harvest, this demonstrates that the feedstock, theoretically, has the potential to be transported internationally. Regarding R_{CO2} ratios, the transport distances are situated between the values provided by the energy analysis and the cost analysis. However, we would like to underline, that a local use of the resource must be encouraged to provide the most important gain, as long distance transport would rapidly decrease the energy and environmental benefit from using the resources.

Table 7: Maximum transport distances of broadleaves wood products and manure. These values represent the values, after which the cost, energy input and CO_2 emissions of transport only, exceed the potential benefit of using the resource.

Name of transport chain	Economic break-even distance [km]	Energetic break-even distance [km]	Ecologic break-even distance [km]
FW--P_H	110	5957	2487
FW-P_L	43	804	275
FW-F	47	803	385
FW-SSWB	58	1993	1002
C-P_L	146	5647	3804
C--P_H	477	7911	5330
C-F	110	3030	2040
LM-P	82	1535	628
LM-F	3	361	145
SM-P	326	3901	868
SM-F	137	3101	668

3.6 Results at cantonal level

3.6.1 Cantonal results for forest wood

When considering different wood types and altitude, an R_C ranging from minimum 4.5 : 1 to maximum 8.7 : 1 can be expected across cantons, which leaves between 82% and 89% of the income for additional production costs and profit. For forest wood, the highest R_C are concentrated in the North and West of Switzerland characterized by a less demanding topography and dominance of broadleaves wood. Due to the higher efficiency of woodchips plants, higher ratios could be expected for all chips-producing cantons (see Appendix F for additional information about wood product, wood species and winter safe storage surface). However, since the ratios behave differently according to wood species, wood product and altitude, it appears that in some cases, high woodchips transport could lead to lower performance indicators. For instance, in the canton Obwalden, woodchips represent 85% of the total energy wood production, 46% of which potentially requiring intermediate winter safe storage (C-WSS), and coniferous wood is dominant. This leads to the lowest economic performance ratio of 4.6 : 1. On the contrary, in the mountainous region of Ticino, high firewood production and a dominance of broadleaves wood result in a higher ratio (see Appendix G for more results). However, the same region scores lowest energetically and environmentally speaking, as firewood requires more energy and is consumed in installations with lower efficiencies. The best regions to produce wood are lowlands with a majority of broadleaves forests and chips production (Geneva, Basel-Land). However, these cantons are very urbanized and increasing harvest is questionable.

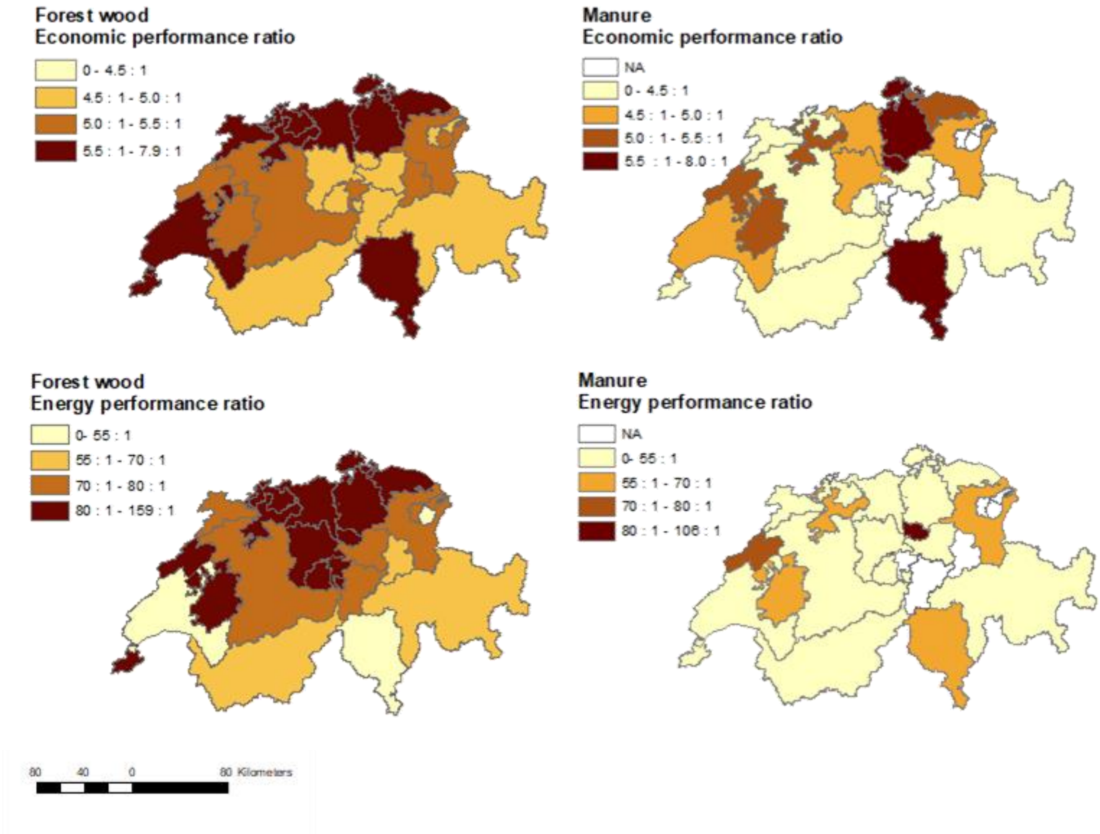

Figure 6: Economic and energy performance ratios in the Swiss cantons. Forest wood ratios represent values on maximum distance estimates

3.6.2 Cantonal results for manure

Using the criteria elicited during the interviews to identify the transport chain utilized for each entry of the manure dataset revealed that liquid feedstock transport occurs in 53% by the mean of professional transporters (LM-P). More precisely, it is the most frequent transport mode for digestate outflows from the biogas plant (59%) but inflows of unfermented manure are led to plants by underground pipes in 55% of the cases. The important use of underground slurry pipes is also positively correlated to better economic, energy and ecologic performance ratios (Appendix H). The frequent use of these modes of transport leads to economic performance R_C ratios of Swiss cantons to be higher than expected from antecedent results (section 3.2.2), the lowest ratio being 3.1 : 1 and the highest 8.0 : 1. The average distance travelled in each canton directly impacted their economic and energy performance. In the canton Solothurn for instance, the average distance between biogas plants and farms was of 2.3 km, and even though 90% of the feedstock was liquid, this led to ratios that are above average (Appendix H). On the contrary, the above average distances that take place in the canton of Bern (16 km for manure and 13 km for digestate), transported mostly by road, leads its three performance indicators to be among the lowest. Unlike forest wood, where costs are the main barrier, the environmental ratio is lower than the cost ratio across all regions. Environmental performance ratios vary between 1.9 : 1 and 3.3 : 1 and (Figure 7) can contradict the economic ratio, as avoided methane emissions are lower for solid manure, but the financial returns are highest. For instance, Schaffhausen has a high economic performance R_C (5.7 : 1) even though distances were significant (25.2 km), which is attributable to the large quantities of solid manure (74%). However, its R_{CO2} of 2.3 : 1 is below average and reflects the important CH_4 emissions during biogas production (2% of CH_4 production) and digestate storage (3%). Additionally, even with conservative assumptions, 1.9 kg of eq-CO_2 are saved for each kg of CO_2 emitted during transport.

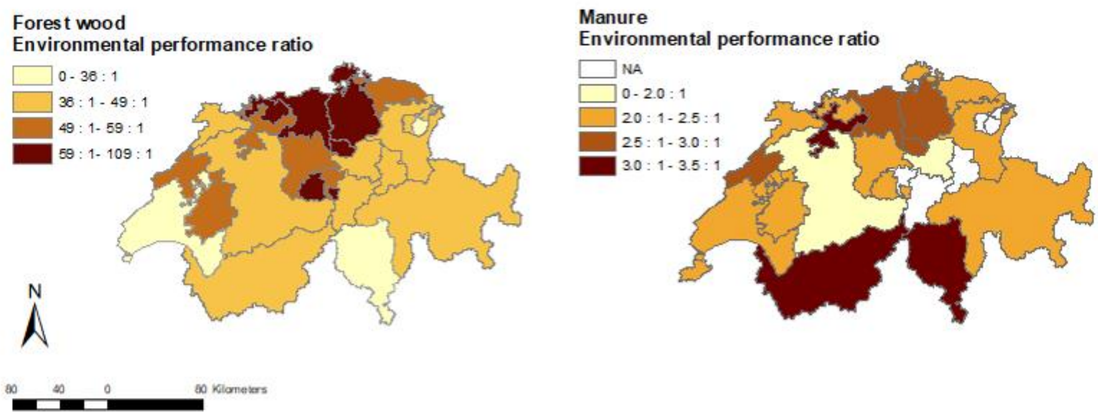

Figure 7: Environmental performance ratios in the cantons

4 Conclusions

The main scientific challenge of assessing biomass transport chains is the large range of possibilities to transport biomass as well as the wide variety of feedstock (Hamelinck et al., 2005; Ko et al., 2018; Thees et al., 2020). As there was no comparable study available in Switzerland that considers the transport of woody and non-woody biomass from economic, energetic and environmental viewpoint, we wanted to gain a deeper understanding of this issue by identifying the most widely used transport chains used for biomass. Due to the lack of existing data, we used mental models approach to capture the plurality of expert knowledge on this topic. A total of 12 plus one additional transport chains, which were most frequently mentioned during the interviews, were then analysed quantitatively further. All identified transport chains occur within the country, as international transport chains are restricted by higher costs than neighbouring countries (Gautschi and Hagenbuch, 2017) and existing regulations (FOEN and FOAG, 2016). In Switzerland, transport mainly occurs by road on distances ranging from 1 to 30 km for forest wood and 5 to 9 km for manure. All interviewed experts recognized the importance of the transport distances, the haulage capacity and the type and bulk density of the feedstock (Allen et al., 1998; Gonzales et al., 2013; Laitila et al., 2016).

In our analysis, liquid manure by underground pipelines was the only transport chain not relying on road infrastructure, although due to topographic and environmental reasons (e.g. water protection areas), their wider use is limited. The transport chains differ in the loading and unloading processes, the use of different vehicles (trucks, tractors) or existing infrastructure (underground pipes). The number of unavoidable empty runs are also particularly significant for the final performance of the different chains. Therefore, optimizing biomass transport eventually implies a better planning of plant locations, road infrastructure adapted to heavyweight transport vehicles in order to increase haulage capacity, and eventually a transition to low- or zero-carbon transport fuels.

Our results show that road transport itself is not the only source of impacts from transporting biomass, as loading and unloading represent a significant part of the final costs, energy and emissions too. Woodchips transport, relying on different logistics processes, is particularly sensitive to coordination, which is a fact known and highlighted by the interviewed experts. Overall, except for agricultural transport of liquid manure, transport always represents at least a third of the potential income that the resource could provide, leaving a modest margin for the other processes. The economic performance of transport in mountainous areas, requiring intermediate storage, is questionable. Representing less than 5% of the primary energy content for all analysed types of biomass, the energy embodied by the road transport is always negligible and cannot be used as an argument against the use of the resource. The environmental cost of manure, as represented in our calculations, is more ambiguous. Here, we point out that the assumed emissions during biogas production (2%) and digestate storage (3%), currently representing a share that is much more important than transport itself, are very conservative. Acknowledging the importance of these leakages, measurements were effectuated directly on plants and effectively represent less than 1% (Ökostrom, 2012). However, even with the potentially overestimated CH_4 losses at the plant, our results suggest that the environmental benefit of manure is two to three times higher than its transport and emissions and therefore, increase the importance of encouraging this sector.

In line with previous literature (Gonzales et al., 2013; Hamelinck et al., 2005; Ruiz et al., 2013), our study confirms that the most important barrier to biomass transport is its costs and not its energy and environmental performance. Maximum transport distances vary widely and highly depend on the transport chains. With regard to costs, they range from 477 km for woodchips to 36 km for firewood; 324 km for solid manure to 3 km for agricultural slurry transport. Since this chain is barely used (1% of the total slurry on our dataset), more restrictive distance limitations than the currently used threshold of 15 km do not seem necessary. Maximum transport distances are extended according to the energy and environmental impact of transport. If only the direct energy inputs and CO_2 emissions from fuel combustion during transport were to be considered, threshold distances would be between 145 to over hundreds of kilometres. However, shifting wood internationally should not be encouraged as the positive energy and environmental impacts would rapidly drop. Furthermore, this research considers only the direct energy use and CO_2 emissions and establishing the effective transport distances should consider the entire life cycle of the machinery, and the remaining production costs in the case of wood. Whilst our results are based on mostly conservative assumptions (high water content for wood and high production emissions for manure), they point out that transport is not the limiting factor for an increased use of Switzerland's local resources.

Swiss regions, with their topographical and geographical variations perform differently. The energy and environmental ratio of forest wood depend on the same variables and, therefore, follow the same trends. There are variations at the cantonal level due to wood types, wood product and altitude, with low altitude and higher proportion of broadleaf and chipping linked to higher ratios. The lowest performance score takes place in mountainous regions and the best in the less hilly ones. However, the less hilly cantons are already quite urbanized and an increased harvest would need to be carefully thought through. For manure, the frequent use of underground slurry pipes positively influences the economic, energy and environmental performance of manure and digestate transport of the cantons, and the overall performance of entire Switzerland. On the cantonal level, the environmental performance can contradict the economic one, as avoided methane emissions are higher for liquid manure, but the returns are lower. By avoiding the emission of 213 kg eq-CO_2 saved per tonne of Dry Matter of liquid manure, greenhouse gas emissions savings of using this agricultural waste are important and should further be encouraged. As costs are the main barrier to its transport, incentives addressing carbon compensations could be provided to exploit the currently underused potential of manure (Burg et al., 2018; Thees et al., 2017)

To conclude:

- Economic, energy and CO_2 performance ratios are described for 12 plus one different transport chains.
- Distances range from 1 to 30 km for forest wood and 5 to 9 km for manure, by road.
- All analysed transport chains are profitable, except for agricultural liquid manure transport for which cost exceed potential income after only 3 km.
- The remaining feedstock can reach destination between 43 and 477 km before its transport outweighs its income.

- Considering energy inputs and CO_2 emissions only, threshold distances lay between 145 to over few thousand kilometres.

- Forest wood cost ratio varies at the cantonal level due to wood types, wood product and altitude, with low altitude and higher proportion of broadleaves wood linked to higher ratios.

- Using agricultural feedstock allows to compensate up to three time the energy of its transport.

- Shifting wood internationally is not recommended as the positive energy and environmental impacts would rapidly diminish.

- Transport is not the limiting factor for an increased use of Switzerland's local resources.

5 Outlook and next steps

This research provides a useful overview of the current state of the art of biomass transport in Switzerland. It shows that it is interesting to transport the feedstock over the estimated distances, except for the underused agricultural slurry tank. Therefore, it is important to continue providing the necessary support to encourage the development of these resources. Also, the deployment of biogas is not only a source of renewable energy but also of a way to reduced GHG emissions from manure management. This study should be used to complement entire logistics chains analysis or it can be a first step for future analysis. Based on these results, optimal locations of new biogas plant facilities could be estimated with precision. The results also provide useful information for feasibility studies and facility managers.

One limitation of our study could be the frequency of occurrence of each forest wood transport chain. In fact, the interviewed experts were unsure when it came to determine the share each chain represents. The Swiss forestry landscape is very diversified and forest districts vary in size, topography and in the share of private/public owners. Furthermore, as the demand creates the offer, the increase demand of woodchips in some regions (e.g. construction of large CHPs such as Aubrugg or Axpo Tegra) might have initiated forestry enterprises' specialization and therefore, processes optimization. The frequency of occurrences we use in the analysis should, therefore, not be identical for each canton. In order to realistically assess the importance of each transport chain, the sectorial benchmark (TBN Forstwirtschaftliches Testbetriebsnetz) could e.g. consult the number of direct consumers of each forestry product.

6 National and international cooperation

This project was initiated at the University of Geneva in the framework of a Master's thesis. It was continued in cooperation with Professor Evelina Trutnevyte of the UNIGE Renewable Energy Systems group. To tackle the challenge of assessing the most important biomass transport chains where there was no data, we appreciated the help and support of Andreas Keel from Holzenergie Schweiz, who provided us with a list of potential interview candidates. Similarly, Urs Baier from ZHAW suggested suitable stakeholders for the manure part. The agricultural biogas plant association Ökostrom patiently answered our questions and provided us with useful insights for the assumptions. Finally, the Federal office for Agriculture (FOAG) provided the HODUFLU dataset, which had not been analysed for transport estimations, and without which such an analysis of manure flows would not have been possible.

7 Publications

An ISI publication will be submitted to the *Journal of Cleaner Production* in August.

This research was summarised in the winter edition of the WSL's internal magazine *Diagonal*:"Wie weit lohnt sich der Transport von Biomasse zur Energiegewinnung ?»

A summary of the forest wood part is being prepared for the magazine Wald und Holz from the association Waldschweiz. Our request is still pending at AgrarForschung for the manure part.

Finally, we presented a poster of this study at the digital conference e-EUBCE, that took place 6-9th July 2020.

Acknowledgements

We would like to thank Andreas Keel from Holzenergie Schweiz for his suggestions how to approach forest wood experts and his pertinent remarks on the report, Urs Baier (ZHAW) for his advice regarding biogas stakeholders and further useful inputs, the Swiss agricultural biogas plants association Ökoström for its expertise, Janine Schweier and Matthias Erni for their valuable inputs on the draft version of the manuscript, and Fritz Frutig and Oliver Thees for their good knowledge of forest wood production practices and Leo Bont for his modelling tips.

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9 Appendix

Appendix A. Vehicle volume and duration of the different transport process steps

Transport chain type	**Transport chain name**	**Volume** (m^3)	**Preparation / waiting time** (min)	**Loading** (min)	**Unloading** (min)
Firewood	*FW - P_H*	9-15 / 2.13	-	10.8[a] / 1.5	10.8 / 12.8
	FW - P_L	14.2 / 2.13	-	17.0 / 1.5	17.0 / 1.3
	FW - F	2.13	-	38.3	38.3
	FW - SSWB	2.13	-	38.3	38.3
Chips	*C - F*	8.9	4	15.8	5
	C - P_L	14.2	9	18.8	9
	C - P_H	22-32	15	42.2[a]	24.1
Liquid Manure	*LM - F*	10	-	5.3	5.3
	LM – P	27	-	11	11
	LM – I	NA	-	-	-
Solid Manure	*SM - F*	25	-	22.8	5
	SM - P	22	-	5	5

note: two values represent two loading processes for indirect transport chains. Forest wood time estimations from Höldrich et al., 2006; Kuptz et al., 2015; Lemm et al., 2018. Manure time estimates from Meier et al., 2017; Tamm and Vettik, 2011

[a] Value for broadleaves wood. Loadtime is 0.017 h/m3 (Kuptz et al., 2015) and the permissible payloads of trucks reduces the transported quantity and herewith the loadtime in the case of coniferous wood

Appendix B. Formula to estimate the avoided emissions of a biogas upgrade into biomethane for fuels

Upgrading biogas into biomethane consists in two step (Adnan et al., 2019): First, the unwanted minor components of biogas must be removed. Then, the surplus CO_2 must be removed. Biomethane is composed of approximately 97% CH_4. We calculated the produced biomethane directly on the HODUFLU dataset. To estimate the emissions we would avoid by using biomethane instead of other car fuels, we used the share diesel of petrol represent in the Swiss car fleet. The formula used was the following:

$$AG_{car} = \frac{Y_{bch4}}{fc_b} * 30\% * G_p * fc_p + 70\% * G_d * fc_d \qquad (7)$$

Where:

AG_{car} = The avoided emissions from biomethane [kg CO_2-eq/t_{DM}]

Y_{bch4} = The biomethane yield per manure type *T* [kg CO_2-eq/t_{DM}]

$fc_{b,p,d}$ = The fuel consumption of cars fueld by biomethane *b* [in kg/km], petrol *p* and diesel *d* [in L/km]

$G_{p,d}$ = The emissions of petrol *p* and diesel *d* [kg CO_2/L]

Appendix C. Costs: additional results

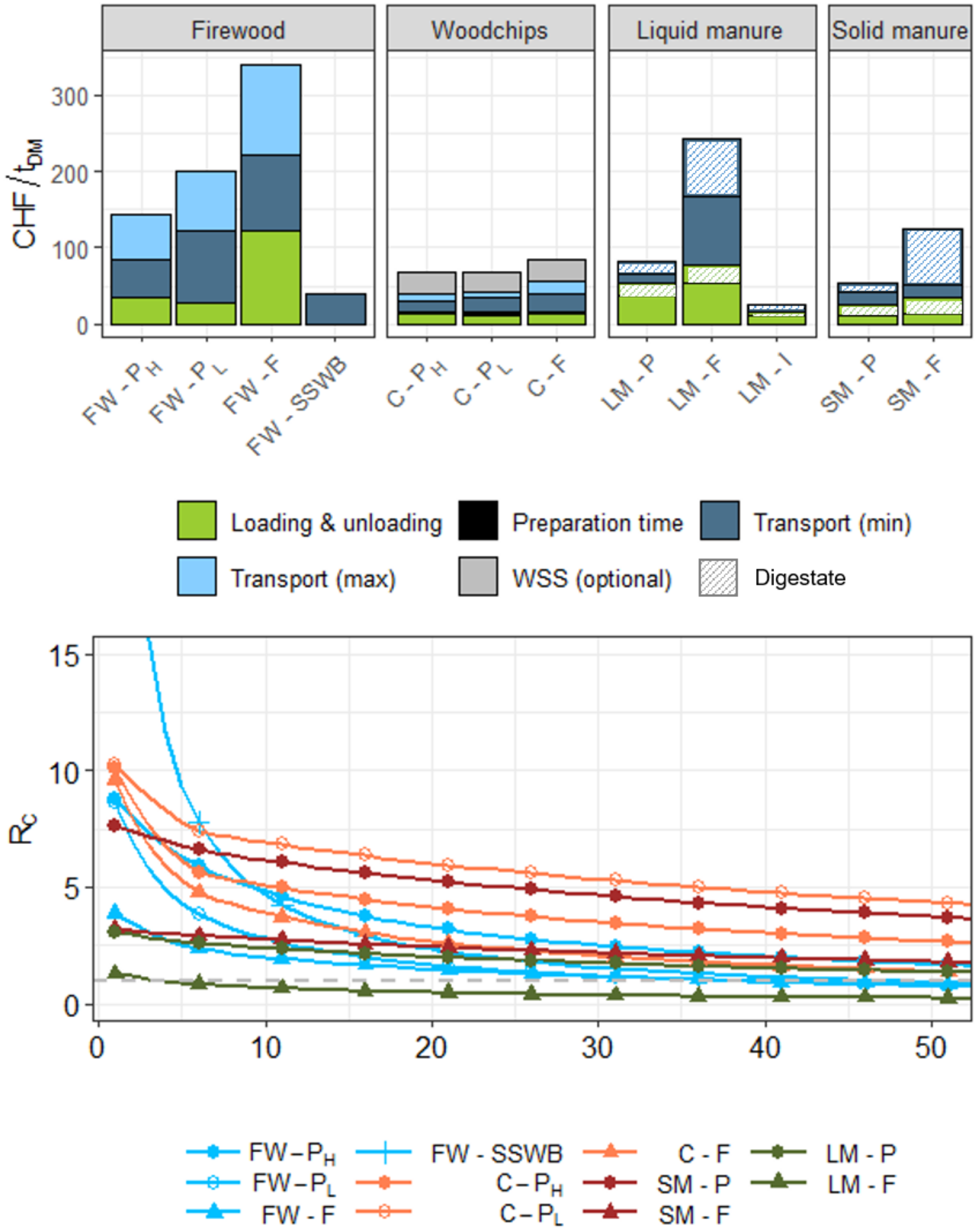

Figure 8: Costs of coniferous wood and manure in CHF/t_{DM} (top) and the R_C economic performance ratio (bottom) with increasing distance to end-consumer. The grey dashed line at one represents the distance after which the potential costs exceed the potential income.

Table 8: Total costs of broadleaves and coniferous wood in CHF/t_{DM} with minimum and maximum distances as well as for solid and liquid manure

	Broadleaves wood			Coniferous wood		
Transport chain name	Total costs with min distances	Total costs with max distances	Total costs max distances + WSS	Total costs with min distances	Total costs with max distances	Total costs max distances + WSS
FW - P_H	58.3	99.1		84.4	143.9	
FW - P_L	83.4	136.0		122.8	200.3	
FW - F	150.2	231.6		221.1	340.9	
FW - SSWB	26.5	26.5		39.0	39.0	
C - F	27.4	38.7	61.3	40.3	57.0	84.2
C - P_L	23.5	28.3	51.0	34.6	41.7	68.9
C - P_H	24.2	32.4	55.1	30.7	39.8	67.0
	Manure					
LM - F	243.6					
LM - I	24.0					
LM - P	81.5					
SM - F	124.3					
SM - P	54.0					

Table 9: Economic performance indicator R_C of broadleaves, and coniferous wood with minimum and maximum distances as well as for solid and liquid manure

	Broadleaves wood			Coniferous wood		
Transport chain name	R_C with min distances	R_C with max distances	R_C with max distances and WSS	R_C with min distances	R_C with max distances	R_C with min distances and WSS
FW - P_H	7.2 : 1	4.3 : 1		6.3 : 1	3.7 : 1	
FW - P_L	5.1 : 1	3.1 : 1		4.3 : 1	2.7 : 1	
FW - F	3 : 1	1.9 : 1		2.5 : 1	1.6 : 1	
FW - SSWB	11.6 : 1	11.6 : 1		9.3 : 1	9.3 : 1	
C - F	8.6 : 1	7.2 : 1	4.5 : 1	6.1 : 1	5.1 : 1	3 : 1
C - P_L	8.4 : 1	6.3 : 1	4.8 : 1	6.9 : 1	5.3 : 1	4 : 1
C - P_H	7.4 : 1	5.2 : 1	3.1 : 1	5.3 : 1	3.7 : 1	2.1 : 1
	Manure					
LM - F	0.9 : 1					
LM - I	8.9 : 1					
LM - P	2.6 : 1					
SM - F	2.7 : 1					
SM - P	6.1 : 1					

Appendix D. Energy: additional results

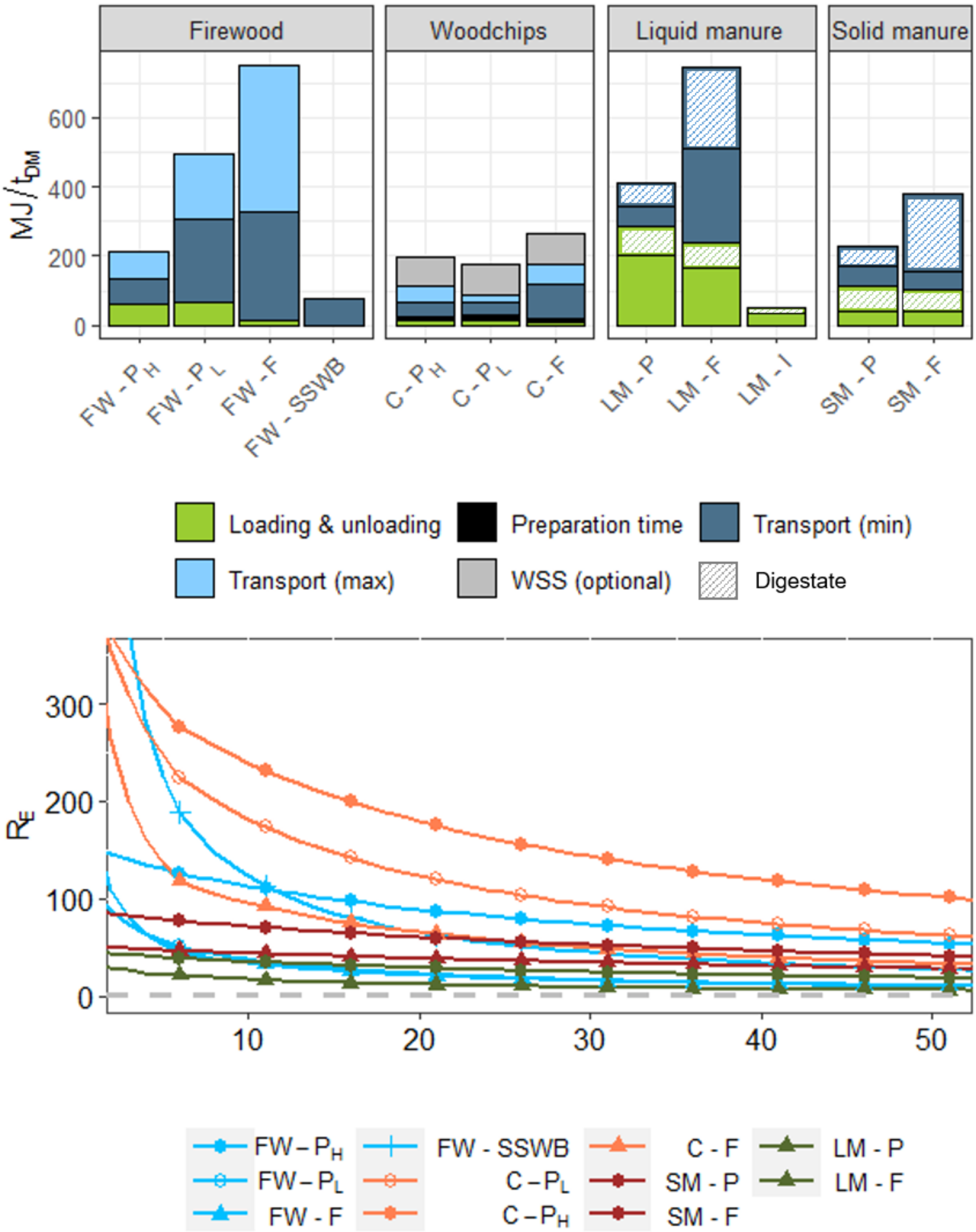

Figure 9: Energy input of coniferous wood and manure in MJ/t_{DM} (top) and the energy performance ratio R_E (bottom) with increasing distance to final consumer. The grey dashed line at one represents the distance after which the energy input exceed the primary energy contained in the resource.

Table 10: Total energy input of broadleaves and coniferous wood in MJ/t_{DM} with minimum and maximum distances as well as for solid and liquid manure

	Broadleaves wood			Coniferous wood		
Transport chain name	Total energy input with min distances	Total energy input with max distances	Total energy input with max distances + WSS	Total energy input with min distances	Total energy input with max distances	Total energy input with max distances + WSS
FW - P_H	92.9	148.7		133.2	212.7	
FW - P_L	208.8	336.0		307.4	494.7	
FW - F	222.5	511.1		327.6	752.6	
FW - SSWB	52.2	52.2		76.9	76.9	
C - F	80.9	121.0	187.7	119.1	178.2	264.0
C - P_L	44.7	60.7	127.3	65.8	89.3	175.1
C - P_H	55.8	96.8	163.5	67.9	113.4	199.1
	Manure					
LM - F	744.4					
LM - I	48.7					
LM - P	410.7					
SM - F	124.3					
SM - P	54.0					

Table 11: Energy performance indicator R_E of broadleaves, and coniferous wood with minimum and maximum distances as well as for solid and liquid manure

	Broadleaves wood			Coniferous wood		
Transport chain name	R_E with min distances	R_E with max distances	R_E with max distances and WSS	R_E with min distances	R_E with max distances	R_E with max distances and WSS
FW - PH	179.6	112.2		130.6	81.8	
FW - PL	79.9	49.6		56.6	35.2	
FW - F	75	32.6		53.1	23.1	
FW - SSWB	319.3	319.3		226.2	226.2	
C - P_L	348.1	256.3	122.2	247.4	182.1	92.9
C - P_H	278.8	160	95.1	239.7	143.5	81.7
C - F	192.2	128.5	82.9	136.6	91.3	61.1
	Manure					
LM - F	21.5					
LM - I	318.8					
LM - P	39					
SM - F	42.2					
SM - P	70.6					

Appendix E. CO_2 emissions: additional results

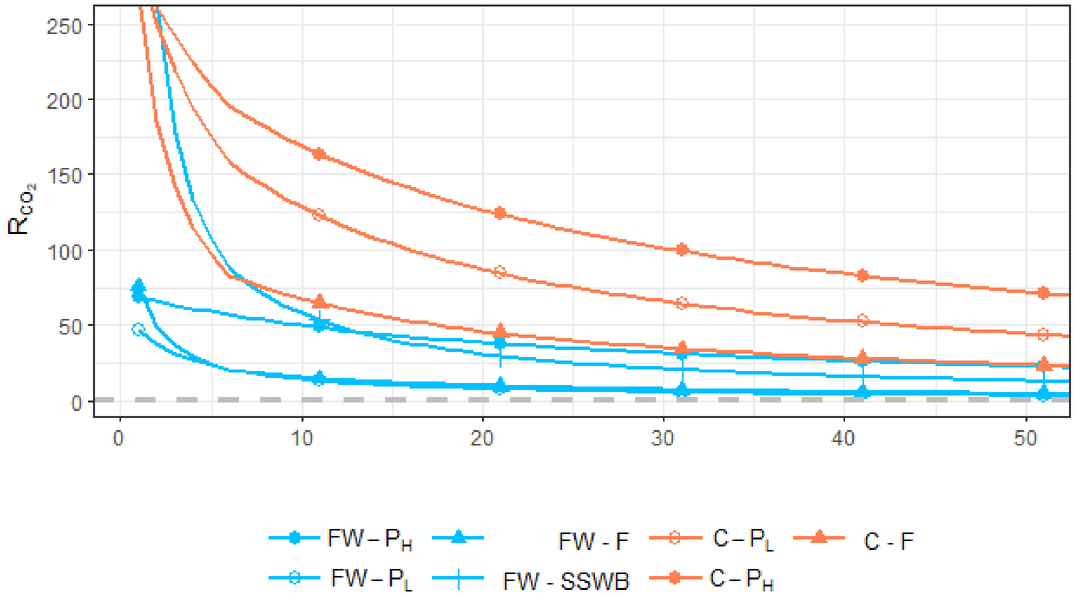

Figure 10: Environmental performance indicator R_{CO2} of coniferous wood with increasing distance to end consumer. The grey dashed line at one represents the distance after which the transport emissions exceed the the avoided emissions.

Table 12: Total CO_2 emissions in kg eq-CO_2//t_{DM} of broadleaves and coniferous wood with minimum and maximum distances as well as for solid and liquid manure.

	Broadleaves wood			Coniferous wood		
Transport chain name	Total CO_2 with min distances	Total CO_2 with max distances	Total CO_2 with max distances + WSS	Total CO_2 with min distances	Total CO_2 with max distances	Total CO_2 with max distances + WSS
FW - P_H	6.8	11.5		15.7	16.4	
FW - P_L	16.7	29.1		42.2	42.9	
FW - F	16.2	37.2		53.5	54.8	
FW - SSWB	3.7	3.7		5.4	5.4	
C - F	5.9	8.8	13.7	8.7	13.0	19.0
C - P_L	3.3	4.4	9.3	4.8	6.5	12.6
C - P_H	4.1	7.0	11.9	4.9	8.3	14.3
	Manure					
LM - F	285.5					
LM - I	108.2					
LM - P	261.2					
SM - F	191.2					
SM - P	180.2					

Table 13: Environment performance indicator R_{CO2} of broadleaves, and coniferous wood with minimum and maximum distances as well as for solid and liquid manure

	Broadleaves wood			Coniferous wood		
Transport chain name	R_{CO2} with min distances	R_{CO2} with max distances	R_{CO2} with min distances and WSS	R_{CO2} with min distances	R_{CO2} with max distances	R_{CO2} with max distances and WSS
FW - PH	89.6	52.9		65.1	38.6	
FW - PL	36.3	20.8		25.7	14.8	
FW - F	37.5	16.3		26.6	11.6	
FW - SSWB	166	166		117.6	117.6	
C - P_L	253.3	186.4	120	180	132.5	90.3
C - P_H	202.8	116.9	86.8	174.4	104.4	76.3
C - F	139.8	93.4	73.2	99.4	64.4	53.8
	Manure					
LM - F	2.6					
LM - I	3.1					
LM - P	2.8					
SM - F	2.3					
SM - P	2.4					

Appendix F. Table of cantonal firewood and woodchips production, and estimated fraction of each wood type and share requiring additional winter storage (C-WSS) (GIS analysis)

Canton	Firewood production [m³]	Woodchips production [m³]	Total surface [ha]	Share of forested area needing WSS	Share coniferous wood	Share broadleaf wood
Aargau	39587	153000	36463	13%	50%	50%
Appenzell i. Rhodes	1102	275	832	48%	74%	26%
Appenzell o. Rhodes	4804	10927	381	45%	78%	22%
Basel land	20003	60170	15518	18%	33%	67%
Basel-Stadt	100	1813	295	10%	29%	71%
Berne	113227	186164	66251	39%	69%	31%
Freiburg	26988	69457	24105	39%	68%	32%
Geneva	619	6938	2191	10%	13%	87%
Glarus	7259	8886	17837	45%	69%	31%
Grisons	59742	69114	185417	48%	86%	14%
Jura	20014	21403	28652	27%	41%	59%
Lucerne	16648	53289	7306	36%	73%	27%
Neuchatel	9319	23011	15930	45%	64%	36%
Nidwalden	5190	10802	3870	42%	68%	32%
Obwalden	5061	29702	16555	46%	71%	29%
Schaffhausen	9822	20426	9001	18%	44%	56%
Schwyz	14499	28653	16016	45%	72%	28%
Solothurn	30245	42103	23039	26%	40%	60%
St Gallen	54008	63941	24152	39%	68%	32%
Thurgau	24749	53106	7195	14%	60%	40%
Ticino	73435	3958	80974	40%	41%	59%
Uri	6402	9027	15191	45%	71%	29%
Valais	25991	26843	99074	48%	82%	18%
Vaud	120273	23362	73650	39%	61%	39%
Zug	4304	20666	4057	36%	70%	30%
Zurich	45088	167782	18042	18%	62%	38%

Appendix G. Cantonal upscaling of forest wood: Economic, energy and environmental performance indicators.

		R_C		R_E		R_{CO2}	
Canton	*Distance*	*min*	*max*	*min*	*max*	*min*	*max*
Aargau		7.9 : 1	5.9 : 1	180 : 1	111 : 1	120 : 1	72 : 1
Appenzell inner Rhodes		7.8 : 1	4.1 : 1	91 : 1	52 : 1	48 : 1	26 : 1
Appenzell outer Rhodes		6.2 : 1	4.1 : 1	119 : 1	76 : 1	76 : 1	48 : 1
Basel Land		8.5 : 1	6.5 : 1	184 : 1	111 : 1	120 : 1	71 : 1
Basel Stadt		8.2 : 1	6.3 : 1	246 : 1	159 : 1	175 : 1	112 : 1
Bern		7.1 : 1	4.7 : 1	125 : 1	77 : 1	78 : 1	47 : 1
Freiburg		6.9 : 1	4.8 : 1	137 : 1	86 : 1	89 : 1	55 : 1
Geneva		8.7 : 1	6.7 : 1	249 : 1	158 : 1	175 : 1	110 : 1
Glarus		7.1 : 1	4.5 : 1	115 : 1	70 : 1	70 : 1	41 : 1
Grisons		6.4 : 1	3.6 : 1	100 : 1	62 : 1	61 : 1	36 : 1
Jura		8.4 : 1	6.3 : 1	138 : 1	80 : 1	82 : 1	46 : 1
Lucerne		6.6 : 1	4.7 : 1	139 : 1	89 : 1	92 : 1	58 : 1
Neuchatel		6.8 : 1	4.7 : 1	135 : 1	86 : 1	87 : 1	54 : 1
Nidwalden		6.9 : 1	4.6 : 1	129 : 1	81 : 1	82 : 1	50 : 1
Obwalden		5.9 : 1	4.3 : 1	141 : 1	96 : 1	97 : 1	65 : 1
Schaffhausen		8.2 : 1	6.1 : 1	160 : 1	95 : 1	102 : 1	59 : 1
Schwyz		6.6 : 1	4.3 : 1	122 : 1	77 : 1	77 : 1	48 : 1
Solothurn		8.4 : 1	6.4 : 1	147 : 1	86 : 1	90 : 1	51 : 1
St. Gallen		7.3 : 1	4.8 : 1	118 : 1	71 : 1	72 : 1	42 : 1
Thurgau		7.8 : 1	5.6 : 1	151 : 1	90 : 1	96 : 1	56 : 1
Ticino		8.6 : 1	6.3 : 1	97 : 1	53 : 1	48 : 1	25 : 1
Uri		6.9 : 1	4.4 : 1	116 : 1	71 : 1	72 : 1	43 : 1
Valais		6.6 : 1	3.7 : 1	102 : 1	62 : 1	61 : 1	36 : 1
Vaud		8.2 : 1	5.1 : 1	96 : 1	54 : 1	49 : 1	27 : 1
Zug		6.6 : 1	4.8 : 1	152 : 1	100 : 1	103 : 1	66 : 1
Zurich		7.5 : 1	5.5 : 1	168 : 1	104 : 1	111 : 1	68 : 1

Appendix H. Cantonal upscaling of manure: Economic, energy and environmental performance indicators

Canton	Share Liquid manure	Average distance manure [km]	Average distance digestate [km]	Share of liquid manure using LM-I	R_C	R_E	R_{CO2}
Aargau	84%	7.3	5.8	78%	4.9	47	2.6
Basel Land	72%	4.6	4.7	0%	4.5	46	2.1
Bern	59%	16	12.6	16%	3.6	24	1.9
Freiburg	85%	4.3	4.3	41%	5.4	56	2.4
Geneva	87%	7.7	7.1	0%	3.1	46	2.3
Grisons	85%	6	7.5	61%	4.2	47	2.5
Jura	68%	4.6	4.3	23%	4.5	47	2.3
Lucerne	78%	10.4	12	87%	4.9	49	2.3
Neuchatel	79%	5.3	5.6	56%	5.3	71	2.7
Obwalden	89%	11.5	11.3	4%	3.2	32	2.1
Schaffhausen	26%	25.2	3.1	70%	5.7	27	2.3
Schwyz	80%	10.1	15.5	0%	3.1	30	1.9
Solothurn	90%	2.3	6.6	100%	5.2	63	3.3
St. Gallen	87%	3.4	7.7	83%	4.9	57	2.4
Thurgau	87%	9.5	7.4	91%	5.5	46	2.3
Ticino	84%	6.5	5.9	90%	6.2	64	3.3
Valais	76%	9.4	11.2	98%	4.3	51	3.1
Vaud	78%	6	4.9	43%	4.8	52	2.3
Zug	92%	5.2	3	100%	8	106	2.6
Zurich	76%	8.2	4.5	89%	6.5	52	2.6