Journal of Cleaner Production 293 (2021) 125971

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Biomass transport for energy: Cost, energy and CO_2 performance of forest wood and manure transport chains in Switzerland

Vivienne Schnorf [a, b, *], Evelina Trutnevyte [b], Gillianne Bowman [a], Vanessa Burg [a, c]

[a] Swiss Federal Research Institute for Forest, Snow and Landscape Research WSL, Research Group Sustainable Forestry, Zürcherstrasse 111, CH-8903, Birmensdorf, Switzerland
[b] University of Geneva, Renewable Energy Systems, Institute for Environmental Sciences (ISE), Section of Earth and Environmental Sciences, Boulevard Carl-Vogt 66, CH-1211, Geneva, Switzerland
[c] Swiss Federal Institute of Technology Zürich (ETH Zurich), Institute of Environmental Engineering, John-von-Neumann-Weg 9, CH-8093, Zürich, Switzerland

A R T I C L E I N F O

Article history:
Received 25 August 2020
Received in revised form
26 November 2020
Accepted 11 January 2021
Available online 23 January 2021

Handling editor Yutao Wang

Keywords:
Biomass
Transport
Bioenergy
Costs
Energy input
CO_2 emissions

A B S T R A C T

Biomass transport represents a significant share of the final price of biomass for energy, and transport itself requires fuel, whose combustion adds to greenhouse gas emissions. We conducted 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. First, we identified the most common transport chains from the supplier to the final consumer in Switzerland, by conducting expert interviews that followed a mental models approach. Then, we quantified the cost, energy and environmental performance of 12 identified transport chains for these types of biomass, using performance ratios. The results show that transport of forest wood is more performant than transport of manure, except when underground pipes are used for liquid manure. In the case of Switzerland, the main barrier to biomass transport is cost rather than energy or emissions performance. Energy required to deliver biomass to final consumers represents between 0.4% and 1.8% of the primary energy contained in the forest wood, and less than 5% in the case of manure. Some forest wood chains attain the maximum break-even transport distances after 36 km only, whereas others could reach over 400 km. Using agricultural transport for slurry should not exceed 3 km from the viewpoint of cost, but could be extended to over 145 km in the case of energy or CO_2 emissions.

1. Introduction

Due to their impact on climate change, greenhouse gas (GHG) emissions need to be cut by transforming the global energy system (Rogelj et al., 2018). In 2009, to comply with the United National Framework Convention on Climate Change (UNFCCC) and the Kyoto protocol, the European Union has started its energy transition and, in 2018, it adopted the most ambitious goal so far of carbon neutrality by 2050, including GHG emissions resulting from land-use change (European Commission, 2018; Loonela et al., 2020). When used sustainably, energy from biomass is carbon neutral and can provide a storable energy solution to phase out fossil fuels (Hiloidhari et al., 2019; Sulaiman et al., 2020). By the end of 2017, modern biomass (excluding traditional use, such as charcoal for cooking) represented close to half of all renewable energy and 5% of total final energy consumption globally (REN21, 2019). With many possible applications, the International Renewable Energy Agency shows that biomass could provide two thirds of the heat and fuel supply by 2050 (IRENA, 2018). The possibility of using biomass for electricity generation, heat and transport led biomass to be considered an important resource for the Swiss energy transition. With the so-called Energy Strategy 2050 (SFOE, 2018), Switzerland established a framework to increase the use of renewable energy to replace soon to be retired nuclear power and, being a federation, delegated the details of its implementation to the cantons (i.e. Swiss states). In 2019, like the European Union, Switzerland also set the goal of carbon neutrality by 2050 (The Federal Council, 2019), making it even more pertinent to develop renewable energy, including biomass.

* Corresponding author. Swiss Federal Research Institute for Forest, Snow and Landscape Research WSL, Research Group Sustainable Forestry, Zürcherstrasse 111, CH-8903, Birmensdorf, Switzerland.
E-mail addresses: vivienne.schnorf@wsl.ch, schnorf.v@gmail.com (V. Schnorf).

https://doi.org/10.1016/j.jclepro.2021.125971

Abbreviations

AD	Anaerobic digestion
bcm	Bulk cubic meter
C	Chips
CHP	Combined heat and power
DM	Dry matter
F	Farmer
FW	Firewood
GHG	Greenhouse gases
LM	Liquid manure
MCF	Methane conversion factor
oDM	Organic dry matter
P	Professional
R_C	Economic performance (cost) indicator
R_{CO2}	Environmental performance (CO_2) indicator
R_E	Energy performance indicator
SM	Solid manure
SSWB	Small-scale wood buyer
Stere	One cubic meter of piled firewood, equivalent to approximately 0.71 solid m^3 of wood
t_{DM}	Tonne of feedstock dry matter
t_{FM}	Tonne of feedstock fresh matter
WSS	Winter safe storage

With an additional 44 PJ that could be sustainably exploited in Switzerland per year, the contribution of biomass resources could be doubled by 2050 as compared to 2020, herewith representing 4% of the country's gross energy consumption (Burg et al., 2018a). Currently representing only 0.2% of the gross energy consumption, manure shows the most significant additional available potential of Swiss biomass (Burg et al., 2019), since only 6% of its sustainable potential (27 PJ per year) is currently being exploited. In Swiss agricultural facilities, animal manure is mainly treated with maximal 20% co-substrates (e.g. catering waste, vegetable and fruit residues) in agricultural anaerobic digestion plants, while industrial anaerobic digestion plants process most remaining organic waste (Schleiss, 2019). Further treatment alternatives, such as direct combustion or pyrolysis of manure (Lazaroui et al., 2020) are not yet developed. Manure is generated in a decentralized manner, which is a challenge for its collection and transport. Nonetheless, the agricultural know-how is already present and biogas development could create job opportunities (Kis et al., 2018; Mohr et al., 2019). In addition to energy generation, methane (CH_4) and nitrous oxide (N_2O) emissions occurring during decomposition are currently representing 19% of the total GHG emission from the agricultural sector in Switzerland and could be significantly reduced by the process of anaerobic fermentation (Burg et al., 2018b). The use of forest wood offers the second-largest additional sustainable energy potential in Switzerland (Burg et al., 2019), where firewood and woodchips 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., 2020). When using forest wood for energy, a potential added value is created because 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 firewood and woodchips led to a rising number of woodchips-based heating and large wood-based Combined Heat and Power (CHP) plants, but at the expense of firewood-based heating (Stettler and Betbèze, 2019). Growing energy crops or energy wood is not practiced in Switzerland.

When envisioning to fully use the remaining potential of forest wood and manure for energy, one frequently addressed question concerns the uncertain impact of transporting biomass. 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; Capponi et al., 2012; Mele et al., 2011) and environmental implications 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 transport space per unit of energy and have a direct negative impact on the processing efficiency of the energy source logistics chain (Allen et al., 1998; Rentizelas et al., 2009; Wolfsmayr and Rauch, 2014). Transport planning optimization is a key issue in the upstream logistics chain (Bravo et al., 2012; Rentizelas et al., 2009). It begins with the loading of the feedstock on the vehicle and ends with the unloading 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. Distances, directly affecting travel time, are a major factor in costs, energy input for transport, and CO_2 emissions (Gold and Seuring, 2011). The chosen transport mode is another contributor to the performance, as it determines the hauled capacity, and therefore the energy content and potential income per load (Hamelinck et al., 2005; Laitila et al., 2016). The importance of all these factors causes the potential transport chains to be numerous and hard to document, frequently leading to data unavailability. Even though transport is expected to significantly affect the economic, energetic and environmental performance of biomass (Gautschi et al., 2017; Hamelinck et al., 2005; Laitila et al., 2016), the specific transport chains of forest wood and manure in Switzerland have not yet been analysed. If a biogas plant is considered as "agricultural" and receives governmental subventions in Switzerland, the maximum transport distance between the feedstock production and energy conversion site must not exceed 15 km (Foen and Foag, 2016). It is, however, uncertain whether this maximum distance is in line with the praxis and similar guidelines do not exist for forest wood. Estimating the maximum transport distances with each mode of transport before becoming economically unviable and energetically questionable would reveal absolute limits and encourage best practice. Maximum distances have been investigated in other countries (Gonzales et al., 2013; Hamelinck et al., 2005; Pöschl et al., 2010), but break-even distances have never been calculated and compared with regard to costs, energy input and CO_2 emissions simultaneously. Finally, we shed light on the regional disparities of transport performance, allowing to put the analysed feedstock within the geographic and administrative boundaries of its current use.

The overall aim of our study is to provide a novel mixed-methods approach to quantify the cost, energy and GHG emissions performance of the key biomass transport chains in Switzerland, focusing on forest wood and manure. This information would not only help to plan the sustainable biomass use in Switzerland and elsewhere, but it would also provide the missing piece in studies on integrating biomass in the whole energy system (Rentizelas et al., 2019; Sasse and Trutnevyte, 2019). More specifically, this study pilots a new methodology and applies it with four objectives:

1) To identify the most important transport chains of forest wood and manure for energy in terms of frequency and amount of resources transported in Switzerland, given the lack of existing data;
2) 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 feedstocks with regard to costs, energy, and CO_2 emissions performance;
4) To upscale these results at the national level and show the regional performance disparities of the Swiss cantons regarding the transport of forest wood and manure.

2. Material and methods

The methodology applied includes four steps (Fig. 1). First, we used a mental models approach to conduct interviews with experts in order to document the major transport chains of forest wood and animal manure in Switzerland, together with their key characteristics and frequencies (Section 2.1). Second, we quantified these major transport chains in terms of costs and energy use, and this information was then used to quantify the direct CO_2 emissions. We used these results to estimate the threshold transport distances of the analysed feedstock (Section 2.2). Finally, the results were scaled up to Switzerland as a whole, including a regional disaggregation that allows to approximate the current situation in each Swiss canton (Section 2.3).

2.1. Mental models interviews

In order to understand the most important transport chains for forest wood and manure we used the mental models approach. Mental models illustrate the way people perceive external reality by using various associations to deduce conclusions (Morgan et al., 2002). These types of interviews are useful when structured data on a topic is scarce and when the overall understanding of the system may differ with various perspectives of interviewees, as it is the case for biomass transport chains (Jones et al., 2011). The interviews further aim at grasping the interviewee's perception of systems 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). Until now, the mental models approach has been mostly applied for interviewing lay people (Volken et al., 2019; Wong-Parodi et al., 2016), but it particularly suits the purpose of our interviews of Swiss biomass experts because of their diversity: from farmers to staff in public institutions. Preliminary discussions with sector's key experts were conducted to determine the interview candidates for the forest wood and manure sectors. The candidates were chosen according to their expertise and role in the sector. Moreover, they are active in different cantons in the whole of Switzerland. The candidates were contacted per e-mail and all respondents were men. 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 were chosen, including private transport enterprises, institutions and researchers. The interviews took place during the summer of 2019 and were audio-recorded for analysis.

An interview protocol was prepared and pre-tested for each feedstock type (supplementary material Section A). The 1-h interviews were semi-structured and composed of two main parts. The first part consisted of a set of open questions aiming to understand the factors influencing transport decisions. The answers were transcribed in influence diagrams, serving as visual representations of each expert's mental model. In the second part, the interviewees were asked to sketch the most important transport chains. This direct elicitation obliged the interviewees to focus on some details that could easily be omitted if the information on the chains was elicited solely orally and this provided immediate means of verification. The first parts of the interviews were transcribed and the summarized versions of the sketches were digitalized. The experts' answers were compared and transport chains that were mentioned at least twice or were of primary importance for at least one of the interviewees were kept for the rest of the analysis. The experts' answers included information on the types of vehicles, the haulage capacity, the final delivery products and volumes, the expected travel distances on trips and empty runs, the service provider and the estimated frequency of occurrence.

2.2. Data description and economic, energy and environmental analysis

The elicited factors that directly influence costs, energy inputs and CO_2 emissions, confirmed the findings from the previous literature: feedstock type and consequently its mass, transport mode and volume, and distance (Laitila et al., 2016; Rentizelas et al., 2009; Searcy et al., 2007). These factors were then used for the calculations. The analysis included all empty runs and, in the case of manure, the additional transport of digestate to the field,

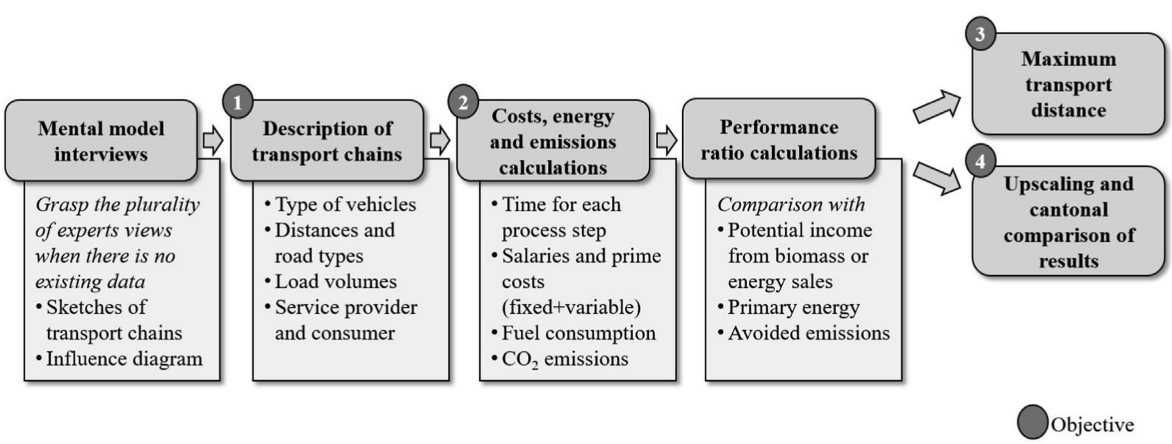

Fig. 1. Method and objectives of the study.

considering mass reduction (supplementary material Section C). The analysis was performed on the initial full load truck or until the initial transported dry matter (DM) is distributed. This is particularly important for manure, as the DM content of inflows into biogas plants differs from the DM content of digestate outflows. Costs were determined by the time necessary for each step of the transport process. Based on the data from literature (Kuptz et al., 2015; Lemm et al., 2018; Meier et al., 2017), the input data regarding transport time to deliver the biomass from the stand to the terminal were confirmed by field trips (Table 1). Machinery costs are taken from governmental publication (EAER, 2018) and include the machine's hourly fixed (investment cost, depreciation, interests and taxes) and variable (fuel and auxiliary materials) costs. Performed yearly, this publication considers individual operation hours, an interest rate of 1.5%, and reflects the values used in the sector in 2018 (Table 2). All values used for the costs of agricultural machineries and trucks, as well as for salaries were confirmed by sectorial experts.

Total distances were estimated by the interviewed experts, whereby the mentioned minimal and maximal values were used. In addition, a record of manure exchange flows between farms or third parties, initially collected to regulate the nutrient flows (FOAG, 2018), allowed to complement information from the interviews. We performed an origin-destination-cost matrix using the Network Analyst extension on ArcGIS 10.6 to calculate the distances between manure suppliers and receivers, along the roads accessible to trucks and tractors (supplementary material Section B.5). We differentiated forest, urban and national roads. The distances on forest roads and urban roads were assumed to be 3 km or 50% maximum of the trip with the remaining distance being travelled on national roads. Driving time, which impacts costs, and fuel consumption, which determines the energy inputs and CO_2 emissions, were estimated according to the road types, driving velocities and distances (Table 2). Hence, CO_2 emissions from transports, derived directly from the vehicle fuel consumption, reflect only the direct emissions while using the machines. According to the national vehicle fleet, all heavy freight vehicles use diesel, and most passenger cars run on petrol (FSO, 2019). Furthermore, the fuel consumption during the loading and unloading processes was assumed to be 75% of the optimal fuel consumption while driving for trucks and 100% for tractors. To complement the environmental analysis of agricultural feedstock, we further considered the additional benefits of anaerobic manure digestion by taking into account the avoided emissions from traditional manure management (MM) practices. The CH_4 and N_2O emitted while storing manure during 30 days, which is the common practice when the feedstock is not brought to a biogas plant, is replaced by a reduced storage duration of 12 days (IPCC, 2019).

To determine the efficiency of the transport, we used the following performance indicators:

Economic indicator: The ratio of the income provided by the biomass resource to the cost inherent to the transport that was used for the economic analysis. This indicator depicts the cost-efficiency of the transport process. Most earlier literature has compared the cost of transport to the final cost of production (Gonzales et al., 2013). Considering today's income from sales of biomass allows to estimate the economic profitability of the process when other production costs are unknown. The economic indicator was calculated as follows:

$$R_C = \frac{I_b}{C_{l(t)} + C_{u(t)} + C_{p(t)} + C_{t(t)}}; \tag{1}$$

in which R_C is the economic performance indicator; I_b is the income from the transported biomass in Swiss francs (CHF) per tonne of DM (t_{DM}); C_l, − the costs of loading the feedstock (CHF/t_{DM}); C_u, − the costs of unloading it (CHF/t_{DM}); C_p, − the preparation costs (CHF/t_{DM}); C_t, − 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, defined as follows:

$$R_E = \frac{PE}{E_l + E_u + E_p + E_t}; \tag{2}$$

in which the energy performance indicator 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 for unloading it; E_p − the energy used during preparation time (MJ/t_{DM}), representing the time necessary for the woodchips transporter to be in the right position next to the chipper; E_t − the energy of fuel consumption to drive the feedstock to final consumers (MJ/t_{DM}).

Environmental indicator: We compared the CO_2 emissions of a reference case, in which the potential final bioenergy produced would be provided by traditional (fossil) energy sources to the emissions of the case of energetic use of biomass resources (Capponi et al., 2012). We assumed that the generated heat would

Table 1
Vehicle load volume, preparation, loading and unloading times. The two values represent two loading processes for indirect transport chains (Höldrich et al., 2006; Kuptz et al., 2015; Lemm et al., 2018).

Chain type	Name of transport chain	Volume (m^3)[b]	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
Woodchips	C-F	8.9	4	15.8[c]	5
	C-P $_L$	14.2	9	18.8[c]	9
	C-P_H	22–32	15	31.8[c,d]	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

[a] Value for broadleaves wood. The permissible payloads and bulk volumes of trucks can reduce the transported volume of the different wood types.
[b] For wood, the volumes are expressed in cubic meter of wood. The actual volume of the woodchips trailer is 25 m^3, 40 m^3 for the woodchips container truck and 90 m^3 for the semi-trailer.
[c] We assumed the professionals to use a Jenz Hem chipper (max. output of 155 bcm/h) and farmers to use the Musmax Wood terminator (max. output of 115 bcm/h).
[d] Value for broadleaves wood.

Table 2
Costs and salaries, vehicle's permissible load, driving velocity and fuel consumption.

	Used in	Permissible load [t]	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[e]	FW-SSWB		0.00		
Machinery				–	–
Roundwood Truck	FW-P_H, C-WSS	12	168.54/134.83	15/35/75	0.52/0.35/0.30
Container Truck 26t	C-P_L, SM-P	22	173/138.40	15/35/75	0.52/0.35/0.30
Semi-trailer Truck 40t	C-P_H, LM-P	27	181.67/145.33	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	1.20/0.48/0.24
Trailer	FW-P_L, FW-F, C-F, SM-F	20	50.00	–	–
Slurry tank	LM-F	10	56.00	–	–
Front loader	FW-P_H, FW-P_L, SM-F	–	12.50	–	–
Piston pump	LM-I	45 m^3/h	13.25	–	20 kV
Pipe[d]	LM-I	–	0.47 CHF/m^3	–	–
Car (petrol) [CHF/km]	FW-P_H, FW-SSWB	–	1.05	35/45/75	0.07/0.06/0.05

[a] Costs of trucks are retrieved from professional's price list and include the driver's cost (−10% profit margin).
[b] Costs while driving and loading/unloading. The charges are higher when driving because of the heavy vehicle tax applying per km.
[c] Driving velocity and fuel consumption on forest, urban and national roads. The hourly fuel consumption was derived from optimal consumption rate (KFZ-Anzeiger, 2010; PTV Planung Transport Verkehr AG, 2009; Rexeis and Hausberger, 2011).
[d] The cost of piston pipes was calculated using a cost of 25 CHF/m for the pipe and 25 CHF/m for digging the trench. Information obtained by a Swiss slurry pipe construction firm and confirmed by a biogas plant manager.

substitute an average fossil fuel-based district heating and that generated electricity would reduce the need for non-renewable power imports (Table 3). In the reference case of manure, the feedstock was assumed not to be brought to a biogas plant, resulting in additional CH_4 emissions from MM. However, the considerable CH_4 losses occurring during the anaerobic digestion of manure (2%) and digestate storage (3%) were taken into consideration (FOEN, 2019). The CO_2 ratio was calculated as follows:

$$R_{CO2} = \frac{AG_{el} + AG_{th} + AG_{mm}}{G_l + G_u + G_p + G_t + G_{mm} + G_s + G_f}; \tag{3}$$

where R_{CO2} is the CO_2 performance ratio; AG_{el} are the avoided emissions from imported electricity in kg eq-CO_2/t_{DM}; AG_{th}, represents the avoided emissions from the fossil fuel share of the Swiss district heating (eq-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}). Concerning only the manure part, AG_{mm} are the 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 the losses from the renewable energy source conversion (kg eq-CO_2/t_{DM}.); G_s the emissions from digestate storage (kg eq-CO_2/t_{DM}.).

Input values for the income, energy content and emissions are shown in Table 3. When analysing forest wood, we differentiated between broadleaves (beech, maple, or ash) and coniferous wood (spruce, larch, or fir), that are the most representative species of Swiss landscapes. They differ in mass, affecting the carried volume and energy content. Woodchips are brought to plants without drying process, and therefore have a water content of 50%, while firewood was assumed to be collected having a water content of 35%. Primary and final energy content of manures was estimated on the provided manure exchange dataset, whereby different types and categories of feedstock, their respective DM and organic dry matter (oDM) were considered (supplementary material Table B1). The final energy output was estimated using CH_4 yield values from the literature (KTBL, 2013), as they consider the CH_4 reduction occurring directly after excretion (Burg et al., 2018b) as well as the biogas plant's efficiency. CH_4 and N_2O emissions from MM were estimated using the methods described in the 2006 IPCC Guidelines (IPCC, 2019). We considered the suggested maximum CH_4 producing capacity as well as system-specific CH_4 conversion factors (MCFs) for the cool climate of Switzerland and N_2O emissions factors (supplementary material Table B1). The conversion

Table 3
Input values for calculations: income, plant efficiencies, energy content, fuels and avoided emissions. The income of firewood is per stere, which corresponds to 0.71 solid cubic meter (m^3). The income from woodchips and manure are per kWh of energy produced, and therefore depend on the energy content and the efficiency of the plant.

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

[a] Price of one stere of coniferous and broadleaves firewood and per kWh of energy produced for woodchips (WaldSchweiz, 2017).
[b] We assumed the heat sold by biogas plants to be at the same price as the income provided by woodchips.
[c] Corresponds to the feed-in tariffs payed-out to biogas plants in 2017 (SFOE, 2017).
[d] With an electrical efficiency of 7% for chips (Stettler and Betbèze, 2019).
[e] Values are measured by the association of agricultural biogas plants (Bolli and Anspach, 2015).
[f] (Hahn et al., 2014).
[g] CO_2 emitted when burning 1 L of fuel.
[h] (Alig et al., 2017; Messmer and Frischknecht, 2016).

efficiencies of the plants reflect current efficiencies in the Swiss market (Bolli and Anspach, 2015; Stettler and Betbèze, 2019).

The above-mentioned indicators further permitted to estimate the maximum transport distance of the different feedstocks without consideration of the remaining production costs, energy input or emissions. These values give an indication of how far a transporter could go before the haulage becomes unprofitable, and more generally, before the transport inputs exceed the potential advantages of using the biomass resource. Calculating with increasing distances allows comparing the different transport chains on equal basis. The break-even point is reached when the value of the specific ratios R_C, R_E and R_{CO2} is below one.

2.3. National upscaling

To upscale the results of forest wood on the cantonal level of Switzerland, we used the forestry statistics, recording quantities of firewood and woodchips harvested (in m^3), combined with a GIS analysis (ArcGIS 10.6) using maps of the forest mix (FSO, 2013) and digital height models. We estimated both the share of each wood type and the amount of wood necessitating intermediate winter safe storage (WSS) (supplementary material Section C). The estimated frequencies of occurrence of each transport chain were averaged and rescaled to 100% by category (firewood and chips). Costs, energy inputs, and CO_2 emissions were calculated according to this assumed frequency for each chain, once with the shortest distance mentioned by experts and also with the longest to provide a performance range. The wood harvest quantities provided the potential income, primary energy and avoided CO_2 emissions (through final energy conversion) to obtain the ratios.

In the case of manure, the influence diagram led to the definition of criteria that allowed to identify the transport used for each entry of the manure exchange dataset. All experts agreed that agricultural transport does not exceed 10 km. As the load volumes of agricultural trailers and professional truck containers were similar, agricultural solid manure transport was, therefore, defined by road distances below 10 km, the remaining solids being attributed to professionals (SM-P). Information on existing underground pipes was gathered directly from the biogas plants. 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. We calculated the costs, energy inputs and CO_2 emissions of transport per tonne DM on the inflow and outflow (digestate) dataset. All values from inflows and outflows (digestate) were summarized per biogas plant leading to the R_C, R_E, and R_{CO2} ratios of the cantons.

3. Results

3.1. Major biomass chains in Switzerland, elicited in mental models interviews

A total of 12 representative transport chains were identified from the expert interviews, of which seven refer to forest wood and five to manure (Fig. 2). If not specified differently, the delivered volume is determined by the vehicle load volume (Table 2) and permissible payload (Table 3). The percentages depicted in Fig. 2 represent the frequency of occurrence of the feedstock type transport chain.

3.1.1. Forest wood transport chains

The elicited transport chains differentiate between firewood and woodchips. The final delivery volume for the three first firewood chain is 3 steres per year (coinciding with the average firewood consumption per installation (Stettler and Betbèze, 2019)), and 1 stere for the small-scale wood buyer (FW-SSWB). The water content is of 35%. In the firewood chains that was most frequently described (FW-P_H), the roundwood is first brought to the enterprise's warehouse in large quantities for further transformation into 0.33 m logs and delivery to the final customer. 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 m bundles at the forest road, maintaining the first load volume to constant 20 steres (14.2 m^3). In the agricultural chain (FW-F), the wood is processed in 0.33 m logs and loaded manually in the trailer directly at the forest road before delivery to the end-consumer by a tractor. Finally, individuals can prepare wood logs themselves manually and transport their wood with private cars and trailers.

The three first woodchips chains (C-F, C-P_L, C-P_H) describe the delivery of fresh chips (50% water content) to customers at different transport distances and using distinctive vehicles. Due to their large volume, the permissible load weight of trucks is rarely attained with 40 m^3 containers, leading professionals to invest in semi-trailer trucks. 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 customer in a repetitive cycle. The container truck and the tractor unload their carriage by tilting the container, while the semi-trailers use a walking floor that pushes the chips in the end-location bunker. The last woodchips chain (C-WSS) is additional to the one mentioned above as it takes place in mountainous areas to secure sufficient provision during the winter when demand is highest and timber is hardly accessible. It consists of transporting the energy roundwood to an accessible storage location, from where the three other chains take place. According to the interviewees, 10% of the future woodchips below 600 m altitude in Switzerland should be carried to such storage places to provide sufficient supply, 25% between 600 and 800 m, and 50% above 800 m altitude.

3.1.2. Animal manure transport chains

Animal manure can be both liquid (LM) or solid (SM) and, therefore, its transport requires different types of trailers. Farmers (LM-F) bring slurry to biogas plants with tractor and tank trailers and return with empty vehicles 60% of the time, meaning that a second empty run is required before bringing digestate to fields (Hersener and Briner, 2019). This high share of empty returns is due to several reasons: first, field fertilization mainly occurs in spring and summer and rarely coincides with the highest manure production taking place in winter as animals spend more time outdoors during summer. Second, a significant motivator to deliver manure to biogas plants is the lack of storage space. Professional slurry transport (LM-P) is the most direct chain, as it avoids all empty runs by optimizing the route and have a load capacity of 27 m^3. Finally, where the infrastructure allows it, 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 is approximately usually1.5−4.5 km, with the longest being 8.5 km.

The digestate outflow service provider coincides with the manure provider, hence, SM carried to the plant by professionals will return to field with the professional liquid means of transport. Agricultural SM transport (SM-F) is done with tractors and trailers and always include an empty run, as convertible trailers for liquid digestate transport are not common. Consequently, an additional empty run between the farm and biogas plant is needed before bringing the slurry to the fields with the 10 m^3 tank trailers. To transport SM, professionals (SM-P) commonly use a container truck

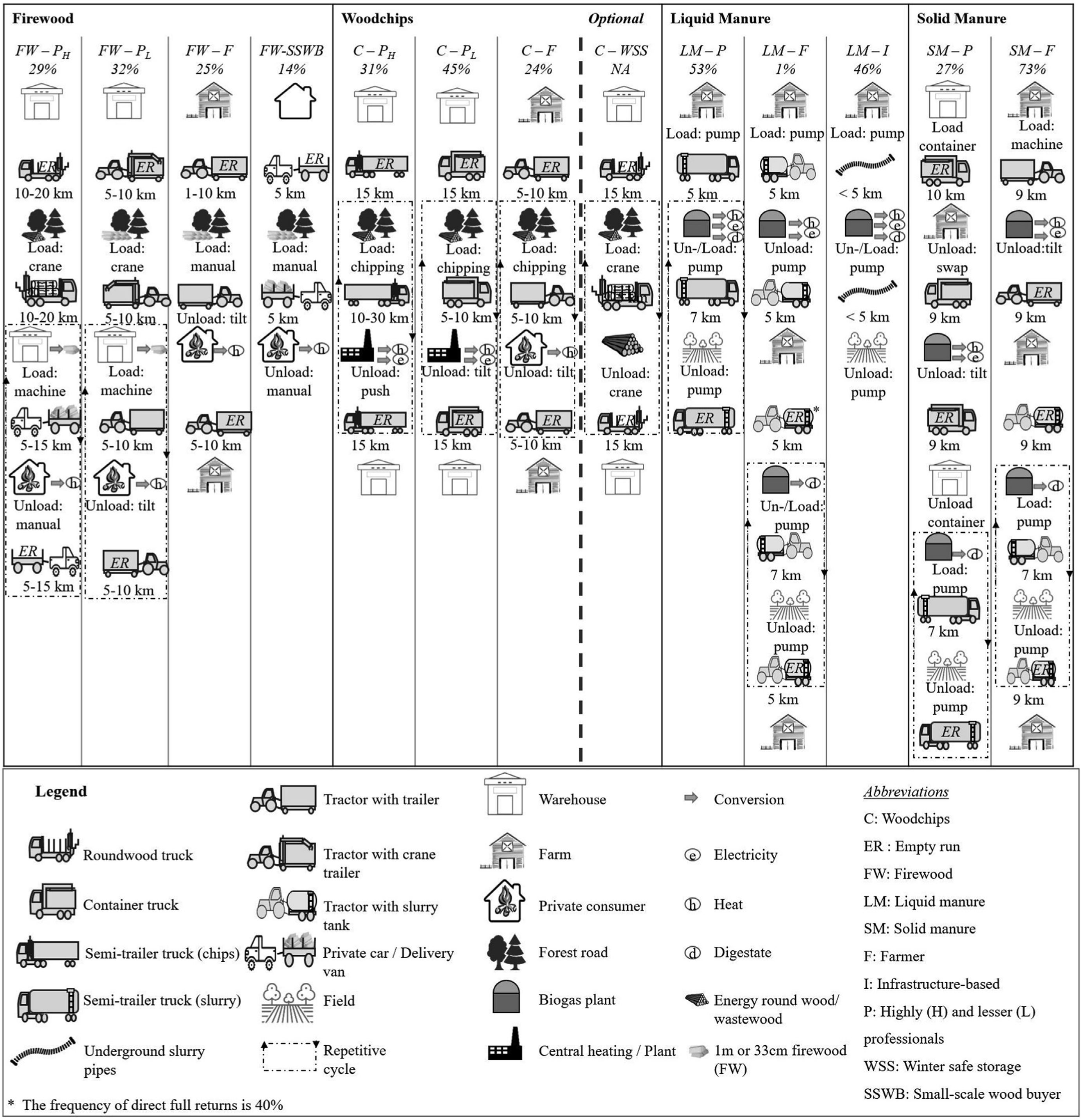

Fig. 2. Forest wood and manure transport chains and expected distances, resulting from the mental models interviews. The percentage below the chain name is the expected frequency, estimated for forest wood and calculated on the dataset for manure. C-WSS represents an optional process taking place in mountainous regions in addition to one of the remaining woodchips transport chains.

(22 m^3), which they exchange with a full container of manure before bringing and unloading it to the plant. The OD cost matrix analysis undertaken on the farms and plants of the dataset revealed that slurry is on average carried for distances of 5.2 km, SM for 9.3 km, and digestate for 7 km.

3.2. Economic evaluation and maximum transport distance

Overall, the costs of the different transport chains vary widely for the 12 analysed chains. Costs range from 24 CHF/t_{DM} for slurry transport by underground pipe (LM-I) to a maximum of 340 CHF/

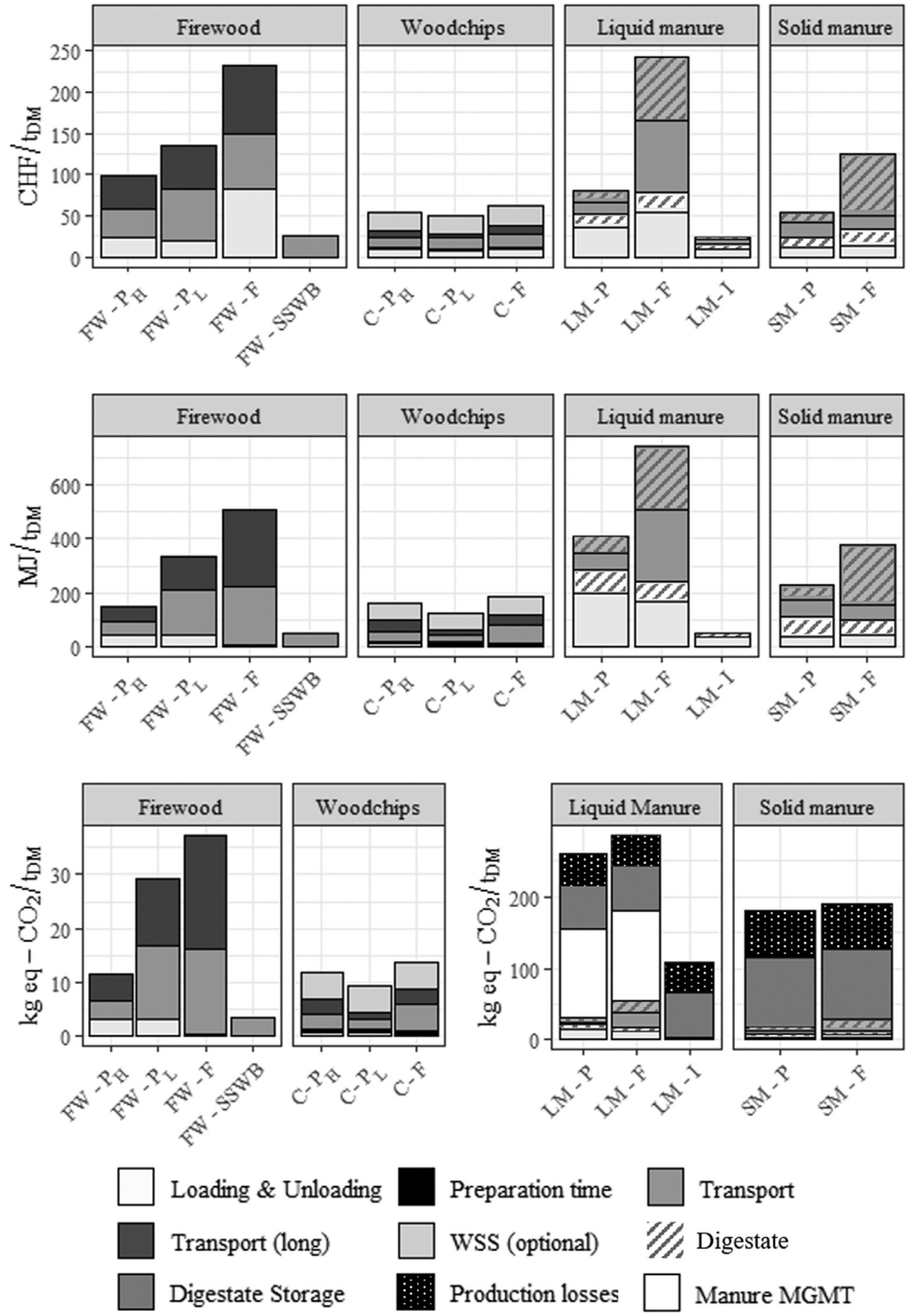

Fig. 3. Costs in CHF/t_{DM}, energy input in MJ/t_{DM} and CO_2 emissions in kg eq-CO_2/t_{DM} of the different chains. Forest wood chains were calculated for broadleaves wood.

t_{DM} for coniferous firewood transported by farmers (FW-F) (Fig. 3). Professional service providers perform better than agricultural ones, because the latter have lower volumes transported, more frequent empty runs, and lower velocities of tractors as compared to trucks. The share of loading and unloading in the final cost of transporting the resource is significant, as it represents between 14% and 56% for wood, and up to 65% in the case of manure.

Unsurprisingly, distances have a significant impact on the final transport costs. The distance range estimated by the experts for forest wood chains leads to an increase of cost of 20–70% of the final transport cost. With costs ranging between 27 and 232 CHF/t_{DM}, firewood transport (broadleaves) is on average costlier than woodchips transport (23–39 CHF/t_{DM}), even in the case of small-scale wood buyers (FW-SSWB), who would be expected to be more performant due to lower mechanization and employment cost. This highlights the importance of the delivered volume, as the low costs of FW-SSWB are cancelled out by the fact that only 1 stere is carried out at the time. Similarly, agricultural firewood chains

(FW-F) is more direct, but delivering 3 steres at once neutralizes the impact of the reduced number of trips. For both firewood and woodchips, loading and unloading represents on average between 22% and 32% of the final transport cost for long and short distances, respectively. Overall, results show that woodchips transport with any type of vehicle is less expensive than firewood, however, additional 22 CHF/t_{DM} must be expected when the energy wood is stored on accessible locations for winter before being chipped (WSS), reducing the final performance of woodchips transport chains by up to 33%. Transport costs per tonne of dry coniferous wood are 23%–47% higher than broadleaves due to its lower mass.

The economic performance ratio R_C of broadleaves wood transport ranges between 1.9 : 1 and 11.6 : 1 (Table 4). With the longest distance estimates of the experts, the final income of transporting broadleaves wood using FW-F is only 1.9 times higher than the cost of its transport, which leaves very little margin for the remaining production cost. In fact, the total income following this transport chain is depleted after only 47 km, whereas it reaches as far as 110 km for the higher professionalised FW-P_H (Table 6). In comparison, broadleaves woodchips return 5.2 to 8.6 times the cost of their transport and could be transported profitably up to 477 km.

The cost of transporting manure varies between 24 CHF/t_{DM} for professional solid manure transport (SM-P) and 244 CHF/t_{DM} for agricultural slurry transport. As for forest wood, loading and unloading manure is nearly as expensive as transport itself (Fig. 3). In fact, pumping 27 m^3 of slurry in a tank lasts nearly 11 min, whereas driving 5 km requires only 7 min by truck. Furthermore, digestate loading represents 30% (underground pipes LM-I) to 75% (agricultural solid SM-F) of the total transport cost. These costs are more important for SM than for LM, as the analysis is conducted until the delivery of the total dry mass, and therefore additional digestate transport occurs for solid manure, also increasing the impact of loading and unloading. Furthermore, since the same service provider is expected for manure and digestate transport, the more important load volume of an agricultural SM load (20 m^3) must be compensated by more frequent slurry tank (10 m^3) runs.

With assumed income of 0.41 CHF/kWh for electricity and of 0.054 CHF/kWh for heat, the average income per dry tonne of solid manure is 327 CHF/t_{DM} in our dataset. This led to an economic ratio R_C of 6.1 : 1 for SM-P and 2.7 : 1 for SM-F, suggesting that professional SM transport is more than twice as performant than agricultural transport (Table 6). Due to lower CH_4 yields, slurry generates on average 210 CHF/t_{DM}. Following this the only not performant chain is agricultural slurry transport (0.9 : 1). In order not to exceed potential income from energy, LM-F including digestate transport should not exceed 3 km. However, not considering bringing fermentation slurry to fields would adjust the economic ratio R_C to 1.5 : 1 and increase transport distance to 10 km. The threshold transport distance of SM-P was 326 km, which was more than twice the distance of SM-F (137 km) (Table 6). Finally, underground pipes had a high R_C of 8.7 : 1, which underlines the importance of using infrastructure-based transport modes, where possible.

3.3. Energy evaluation and maximum transport distances

The energetic performance indicator R_E depicts the relation of the primary energy contained in the feedstock to the direct energy required for its transport. Situated between 23 : 1 and 364 : 1, the R_E of transporting manure or forest wood, were much higher than R_C. This leads to the result that the energy input of transporting manure and forest wood are less important than their costs and that they represent less than 5% of the primary energy contained in the resource.

Following the different transport chains, the energy input per t_{DM} of broadleaves wood was of the magnitude of ten, the lowest being for C-P_L (45–52 MJ/t_{DM}), and the highest for FW-F (222–511 MJ/t_{DM}) (Fig. 3). Resulting ratios R_E were between 33 : 1 and 180 : 1 for consumer good firewood (apart from individual small-scale buyers) and between 134 : 1 and 365 : 1 for woodchips (Table 6). As for costs, intermediate WSS nearly doubled transport's direct energy inputs and significantly reduced R_E by on average 45%.

The best energy performance of manure transport was obtained by underground slurry pipes, as only the electricity for loading and unloading through pumping was considered. The used piston pump transported 45 m^3 of slurry per hour to the fermenter for a capacity of 20 kW, which led to 50 MJ/t_{DM} required and a R_E of 319 : 1. Considering the low quantities of DM transported, agricultural slurry transport required the highest amount of energy (744 MJ/tDM). The energy used by loading and unloading slurry on agricultural tank trailers was more important than transport itself, as we assumed stationary fuel consumption of the tractors to be 100% of the average hourly fuel consumption (12 l/h). However, due to the important content of primary energy, its ratio R_E of 22 : 1 was still significantly above one and remained on this level up to a distance of 361 km (Table 6). The higher average dry matter contained in solid manure (32%) allowed to push the limit to 3900 km.

3.4. Environmental evaluation and maximum transport distances

As only direct emissions from fuel combustion were considered, energy input and CO_2 emissions of forest wood followed the same trend. However, emissions from MM and CH_4 production at the biogas plant were taken into account when assessing manure transport emissions, drastically impacting the results of the agricultural feedstock. For all transport chains, the environmental performance ratio R_{CO2} was lower than the energy performance ratio, since the avoided emissions depend on the feedstock conversion efficiency.

The lower conversion efficiency of firewood, as compared to woodchips, also increased the gap between the environmental ratio R_{CO2} of the two resources. In fact, except for the private small-

Table 4
Economic, energy and environmental performance ratios of the different forest wood transport chains with longest and shortest distances mentioned by the experts.

	Economic performance indicator (R_C)		Energy performance indicator (R_E)		Environmental performance indicator (R_{CO2})	
Name of transport chain	Broadleaves wood	Coniferous wood	Broadleaves wood	Coniferous wood	Broadleaves wood	Coniferous wood
FW-P_H	4.3–7.2	6.3–3.7	112–180	131–82	53–90	39–65
FW-P_L	3.1–5.1	4.3–2.7	50–80	57–35	21–36	15–26
FW-F	1.9–3	2.5–1.6	33–75	53–23	16–38	12–27
FW-SSWB	11.6	9.3	319	226	166	118
C-P_L	7.2–8.6	6.1–5.1	256–348	247–182	186–253	133–180
C-P_H	6.3–8.4	6.9–5.3	160–279	240–144	117–203	104–174
C-F	5.2–7.4	5.3–3.7	129–192	137–91	93–140	64–99

scale wood buyers (FW-SSWB), broadleaves firewood transport chains emitted between 7 kg CO_2/t_{DM} for the highly professionalised chain FW-P_H and 37 kg CO_2/t_{DM} for FW-F, and consequently had R_{CO2} between 90 : 1 and 16 : 1 (Table 5). In turn, emissions of chips transport range between 3 kg CO_2/t_{DM} (C-P_L) and 14 kg CO_2/t_{DM} (C–F), which resulted in R_{CO2} of 253 : 1 to 93 : 1. Winter safe storage added 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%.

Transport emissions of animal manure were negligible as compared to CH_4 emissions before, during, and after its fermentation. Based on the dataset, liquid manure is estimated to 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 agricultural and professional SM transport was of 2.3 : 1 and 2.4 : 1 (Table 5). Accordingly, higher avoided MM emissions and lower methane outputs led to a better performance of slurry on distance estimates from the dataset.

Maximum transport distances due to CO_2 emissions were between the cost-restricted and the energy-restricted ones (Table 6). With increasing distance to the final consumer, professional firewood transport chain (FW-P_L) of broadleaves wood should not exceed 275 km and only 194 km for coniferous wood. This resulted in the least performant wood transport chain, and coming right after the slurry transport with a tractor. In comparison, woodchips could be transported over a distance of 5000 km if purely environmental aspects would be considered.

3.5. Cantonal upscaling of the results

According to the answers provided by the experts, the largest amount of firewood wood is transported by professionals with tractors and trailers (FW-P_L), while woodchips are carried to consumers by container trucks (C-P_L) (Fig. 2). Similarly, the criteria elicited during the interviews were used to identify the transport chains utilized for each entry of the manure dataset. They revealed that liquid feedstock transport occurred mostly by means of professional transporters (LM-P) and solid manure with agricultural ones (SM-F) Applying the estimated frequencies on each canton, our upscaling analysis showed that economic, energy and environmental performance of forest wood and manure did not follow the same trends across the country (Figs. 4 and 5). For instance, most of the cantons with high economic performance ratio for energy wood seems to be concentrated in the North and the West of Switzerland, whereas manure transport performs averagely in these regions. Following our results, forest wood chains always perform better in terms of energy input and CO_2 emissions than manure chains. However, the results are less clear when it comes to costs, as the frequent use of underground pipes in some cantons (e.g. Zurich, Zug) leads to a better economic performance of manure transport compared to forest wood on maximum distance (supplementary material Tables C1 and D1).

When considering different wood types and altitudes, an economic performance ratio R_C ranging from minimum 4.6 : 1 to maximum 8.7 : 1 can be expected across cantons, leaving between 82% and 89% of the margin for additional production costs and profits. Since woodchips perform generally better, higher cost ratios could be expected for chips-producing cantons. But since the ratios behave according to the wood types, wood products and altitudes, it appears that in some cases, high levels of woodchips transport could lead to lower efficiencies. In the canton of Obwalden, woodchips represent 85% of the total energy wood production, 46% of which potentially requiring intermediate WSS, leading to the lowest income-cost ratio of 4.6 : 1 to 5.9 : 1. On the contrary, the mountainous canton of Appenzell Innerrhoden attained a relatively high R_C of 5.3 : 1 to 7.8 : 1 due to the large amount of firewood production. However, this same canton scores lowest from the energetic and environmental perspective, as firewood requires more energy and it is consumed in installations with lower efficiencies.

The frequent use of underground pipes to transport slurry leads the Swiss economic performance ratio R_C of manure to be higher than expected from antecedent results (Section 3.2) with the lowest cantonal ratio being 3.1 : 1 and the highest one 7.9 : 1. Unlike forest wood, where costs are the main barrier, the environmental performance ratio of manure is lower than the cost ratio across all regions (Fig. 5). In some regions, the environmental performance even contradicts the economic one. This is due to the fact that the methane yield is more important for solid manure, leading to more leakages during biogas production. Solid manure also provides less manure management emissions reduction due to lower MCF (Supplementary Material Table A1). Therefore, cantons with higher amounts of solid manure will have a lower environmental ratio, but they also generate more returns and have higher economic ratio. For instance, the region of Ticino in the South has a ratio R_C of 6.3 : 1, but its R_{CO2} is of 1.5 : 1 only.

4. Discussion

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 an 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 a 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 neighboring countries (Gautschi and Hagenbuch,

Table 5
Economic, energy and environmental performance ratios of the different manure transport chains.

Name of transport chain	Economic performance indicator (R_C)	Energy performance indicator (R_E)	Environmental performance indicator (R_{CO2})
LM-P	2.61	39	2.8
LM-F	0.87	22	2.6
LM-I	8.9	319	3.1
SM-P	6.1	71	2.4
SM-F	2.65	42	2.3

Table 6
Maximum transport distances according to costs, energy and CO_2-emissions performance of biomass transport.

Name of transport chain	*Type*[a]	Economic break-even distance [km]	Energetic break-even distance [km]	Environmental break-even distance [km]
FW-P_H	*SW*	92	4213	1755
FW-P_H	*HW*	110	5957	2487
FW-P_L	*SW*	36	568	194
FW-P_L	*HW*	43	804	275
FW-F	*SW*	37	567	271
FW-F	*HW*	47	803	385
FW-SSWB	*SW*	46	1412	710
FW-SSWB	*HW*	58	1993	1002
C-P_L	*SW*	191	3832	2700
C-P_L	*HW*	286	5647	3804
C-P_H	*SW*	437	7135	5028
C-P_H	*HW*	477	7911	5330
C-F	*SW*	74	2054	1446
C-F	*HW*	110	3030	2040
LM-P	*LM*	82	1535	626
LM-F	*LM*	3	361	145
SM-P	*SM*	324	3901	865
SM-F	*SM*	136	3101	665

[a] SW = Coniferous wood HW= Broadleaves wood.

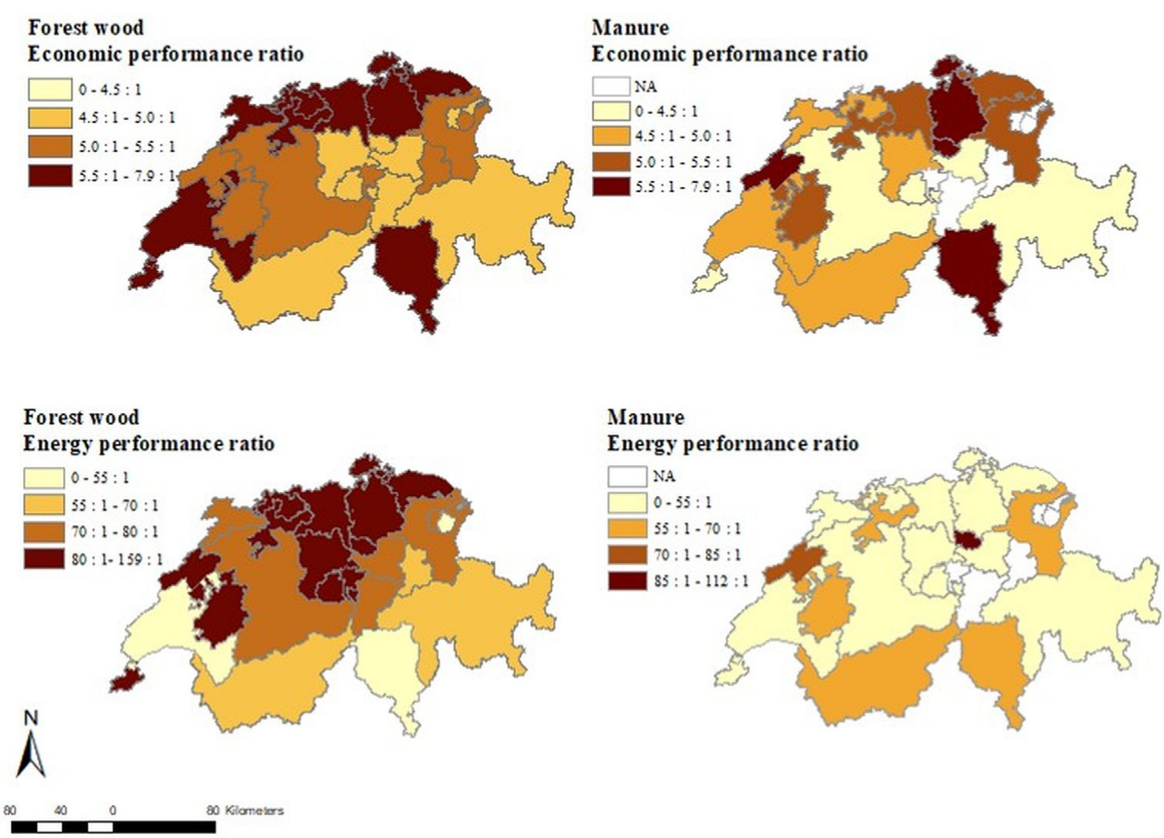

Fig. 4. Economic and energy performance ratios in the Swiss cantons.

2017) and existing regulations (Foen and Foag, 2016). 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. 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

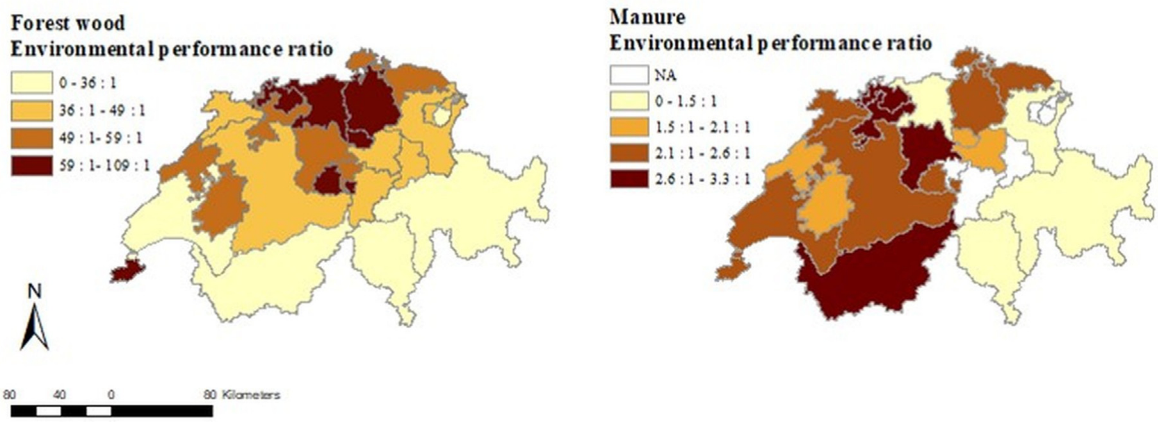

Fig. 5. Environmental performance ratios in the Swiss cantons. Due to additional emissions from manure management, methane production and digestate storage, the values for manure are much lower than for forest wood and necessitate different scales of analysis.

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 it is 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, in some countries recent plants have more restrictive guidelines, where measurements are frequently effectuated. Such additional information could be used in future analysis to gain precision on effective carbon compensations. 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 underline 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 to at least 360 km according to energy and 145 km to environmental impact. The energy break-even distance of forest wood being close to 8000 km indicates that, looking only at transport, exporting energy wood to neighboring countries, which may sometimes be necessary due to market conditions, must not be seen as energetically or environmentally inefficient. However, it should be noted that no other processes of the supply chain were included in the calculation and the threshold distance for the full supply chain might be much shorter. Information on threshold transport distances can be used for optimal plant location and feasibility studies, as they provide the radius of efficient biomass supply.

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. The lowest performance score takes place in mountainous regions and the best in the less hilly ones. However, the latter cantons are already quite urbanized and an increased harvest would need to be carefully thought through. However, the exploratory nature of this study implied a limited number of interviewees and did not allow to specify the importance of each forest wood transport chain in different cantons. Large-scale surveys to forestry enterprises could be used to gain a deeper understanding of these differences. 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., 2018b; Thees et al., 2017). In the future, this study could be complemented by an uncertainty analysis that would consider the changing availability of the feedstock due to societal factors (e.g. less cattle due to vegetarian diets) or climatic factors (e.g. slower wood growth) (Speirs et al., 2015). The creation of different scenarios should also examine the possibility of expanded implementation of recent technologies, such as forest wood pelletizing and enhanced manure separation, which would lead to transport chains that are currently neglected.

The transport and environmental impacts of ashes from wood combustion were not considered, whereas manure transport also considered digestate transport. This is due to the fact that ashes represent an insignificant share of all transports (Misra et al., 1993) and that filter technologies on recent wood installations capture significant amounts of particle emissions. We decided to include the transport of digestate in calculations in our system boundaries in order to provide a methodology that could be replicable in different countries and with different types of installations. In this study, only agricultural biogas plants were analysed. In Switzerland, the current law ensures that these installations must be situated in a close neighborhood of farms, leading to minimal additional transport. However, the larger is the installation, the larger is its service area to collect feedstock and the further are the fields to spread the digestate. In this case, the transport of fermentation substrate becomes an unavoidable part of the process and should not be ignored. Finally, our study considers only direct energy inputs and greenhouse gas emissions and does not follow a life cycle perspective. In order to have a better understanding of biomass transport for energy, these findings could be complemented by further assessment of the impact of the infrastructure, machinery and the entire logistics chain.

5. Conclusions

Expected to significantly impact the economic, energy, and environmental performance of the biomass resource, biomass transport chains must be investigated in order to increase the role of biomass and to decarbonize the energy sector. In a case study on Switzerland, we identified seven main transport chains for forest wood and five for manure, which are the two biomass resources that still possess the highest unexploited sustainable potential in Switzerland. To our knowledge, our choice of mental models interviews has never been used in the context of logistics chains, and we show that it allows to elegantly elicit the key transport chains and their characteristics and to capture the complementary points of view of different experts. This methodology is especially applicable when current practices of biomass transport are undocumented or unknown. In Switzerland, the main transport mode is by truck on the road and transport distances range from 1 to 30 km. 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. Despite the wide range of results, all transport chains can be considered economically profitable, except for agricultural liquid manure transport for which cost exceed potential income after only 3 km. The remaining feedstock can reach destination between 36 and 477 km. The energy required for transport represents between 0.4% and 5% of the energy embodied in the resource. If the energy produced was used to substitute fossil fuel-based generation of electricity and heat, using agricultural feedstock allows to compensate up to three times the emissions of its transport, even when considering very conservative CH_4 emissions during biogas production. This demonstrates that cost is the only barrier to transport biomass for energy and highlights the relevance of its use to tackle current environmental challenges. As it can be expected that only costs significantly differ between this case study of Switzerland and other countries in Europe, the energy and environmental results would be applicable to the other countries using similar transport chains. The results can serve as a start for deeper investigations of biomass logistics chains, such as using life-cycle assessment or life-cycle costing methodologies, or as a basis to identify optimal plant locations. Therefore, they provide useful insights to decision-makers and practitioners.

CRediT authorship contribution statement

Vivienne Schnorf: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Evelina Trutnevyte:** Conceptualization, Supervision, Methodology, Writing - review & editing. **Gillianne Bowman:** Conceptualization, Validation, Resources, Writing - review & editing, Project administration. **Vanessa Burg:** Conceptualization, Funding acquisition, Resources, Supervision, Validation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research project was financially supported by the Swiss Federal Office of Energy (SFOE), the Swiss Federal Institute WSL (internal call) and was part of the Swiss Competence Center for Energy Research SCCER BIOSWEET. We would like to thank Andreas Keel from Holzenergie Schweiz for his suggestions how to approach pertinent forest wood experts, Urs Baier (ZHAW) for his advice regarding biogas stakeholders and further useful inputs, the Swiss agricultural biogas plants association Ökoström Schweiz 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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.125971.

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