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Title: Mountain forest wood fuel supply chains: comparative studies between Norway and Italy

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Abstract: Case studies of mountain forest wood fuel supply chains from Norway and Italy are presented and compared. Results from previous studies in which greenhouse gas emissions and costs were evaluated using life cycle assessment and cost analysis respectively, are compared. The supply chain is more mechanized in Norway than Italy. Steeper terrain and low road density partly explain the persistence of motor-manual felling in the Italian case. Mechanized forest harvesting can increase productivity and reduce costs, but generates more greenhouse gas (GHG) emissions than motor-manual harvesting. In both cases, the main sources of GHG emissions are truck transportation and chipping. The total emissions are 22.9 kg CO2/m3s.o.b. (Norway) and 13.2 kg CO2/m3s.o.b. (Italy). The Norwegian case has higher costs than the Italian one, 64 €/m3s.o.b. and 41 €/m3s.o.b. respectively, for the overall supply chain. The study shows that mountain forests constitute an interesting source for fuel biomass in both areas, but are a rather costly source, particularly in Norway. The study also exemplifies the care needed in transferring LCA results between regions and countries, particularly where forest biomass is involved.

Response to Reviewers: REVIEWER 1
1. Chapter Introduction is too long, some parts are obvious knowledge (eg. rows 43-53) or have little connection with the aims of the article (eg. 89-91). I would suggest to authors to look through this chapter again and to leave only those parts which really are important for this article.
ANSWER 1. The authors have deleted these lines:
a) from 45 to 54, since they refer to general knowledge about fossil fuels as net contributors of CO2.
b) from 89 to 91, because they contain general information about the functionality of mountain forests
c) from 95 to 97, because they refer to general knowledge on climate modelling.

2. 118 row. It is really truth that in all cases clear cuttings are forbidden in mountain forests in Norway and in Italy? Reviewer has visited some sites in Norway that were clear cut.
ANSWER 2. Italy:
Italian silviculture is largely based on continuous cover forestry (CCF) and applies selection cutting as the main prescription (Spinelli and Magagnotti 2013). Clearcuts are only applied to coppice forests, on relatively small areas (<5-10 ha, depending on regional regulations). No clearcuts larger than 0.5 ha are allowed on high forests, with the exception of salvage cuts, whose extension depends on the surface area actually damaged.

In the introduction we added the following text: “Italian silviculture is largely based on continuous cover forestry (CCF) and applies selection cutting as the main prescription (Spinelli and Magagnotti 2013). No clearcuts larger than 0.5 ha are allowed on high forests, with the exception of salvage cuts”.
Reference:
Spinelli, R., Magagnotti, N. (2013) The effect of harvest tree distribution on harvesting productivity in selection cuts, Scandinavian Journal of Forest Research, 28:7, 701-70
Norway: mountain forest are harvested through small clear cuts. 5-10 trees should be left per ha in the felling areas (page 44: forest management guidelines European forest institute).
According to the Standard for sustainable forest management: “The harvesting methods for spruce must as far as possible follow the “mountain forest selection cutting system”. Small-scale clear-cutting and smaller seed tree stand felling should be used as far as possible to promote regeneration in the pine forest”.
Specific rules and environmental restrictions characterize the management of these Norwegian forest stands.
In the revise manuscript version we added the following text: “ Selective cutting and small-scale clear cutting or group cutting, clear cutting of areas from 0.2 to 0.5 ha, are the conventional harvesting systems for mountain conditions”
3. The study objects (131-135) could be described in Chapter 2.
ANSWER 3. Moved to chapter 2
4. Chapter Material and Methods
I want to ask the authors to describe more clearly the study objects and under what conditions the study results were obtained. The case studies were done under different conditions, production systems, so it very important to know what was the logging, chipping, and transportation conditions, what machines were used, what salaries where used in calculations and so on. Are these chip production systems usual in case of Italy and Norway?
ANSWER: 4. Italy: The system described is quite typical for the Italian Alps, and in general of modern day Alpine logging (Spinelli et al. 2007).
Reference:
Spinelli, R., Nati, C., Magagnotti, N. Recovering logging residue: Experiences from the Italian Eastern Alps. (2007) Croatian Journal of Forest Engineering, 28 (1), pp. 1-9.

Norway: harvester and forwarder are tipically used in logging operations in Norway. Forest residues are usually left at the stand, but in our case study we assume them to be bundled. Transport to Sweden usually occurs by train as assumed in or case study.

We added in the revised text: “The object of this study is to compare two real-life examples of forest fuel supply chains in two mountainous countries, Norway -Hedmark/Oppland counties (case a)- and Italy -Fiemme Valley (case b). In the text, the terms “Norwegian case” and “Italian case” indicate generically these two regions.
The system described is quite typical for the Italian Alps, and in general of modern day Alpine logging (Spinelli et al. 2007), while the Norwegian system represents common praxis among theoretical elements. At the same time, these case studies offer contrasting economic and cultural environments, as expected for northern and southern Europe, respectively”.

Regarding chip production system, please look at the answer 62 to reviewer III below (chipping at the landing/terminal versus chipping at the plant).
For more information, please refer to appendix 1.
5. 156 row. What is relatively flat? Steep?
ANSWER:5. Definition of flat terrain: “the eastern region of Norway, Hedmark and Oppland are characterized by mostly high plateaus located at high altitude, but characterized by minimum slope.

Differently it is the situation on the western coast where the forests are located in steep terrains surrounded by fjords"

Definition of steep terrain in Italy: There is not a standard definition for steep terrain, but we can refer to terrains of the third class of Hippoliti, having a slope >40%.
In the text: "having a slope > 40% according to Hippoliti classification"
Reference:
Hippoliti G. 1983. Appunti di Meccanizzazione forestale. Ed. Università di Firenze. Facoltà di Agraria. Firenze (Italia).

6. I would recommend removing all discussions from this sector (eg. Rows 147-153, 164-172), and describe very clearly the methods (only once one method) which was used in this study
ANSWER:6. The authors have deleted
lines 147-153 and lines 164-172, because they agree with the need for reducing the length of the article and because these lines provide generic information.
For the methodology we refer to lines 140-152.
7. 176-179 rows. I would prefer that in scientific papers the things would be named as they are. Nor climate change neither GWP were measured in this study, but only GHG.
ANSWER:7. The characerization model for GHG emissions is GWP. This is a terminology accepted by the scientific commmunity and very common in LCA studies.
8. 202-204 rows. Why artificial regeneration was evaluated in case a, if the authors declare that natural regeneration was more common in Norway. (I guess that statistics about regeneration method should exists)/ There is no explanations how regeneration costs and GHG was allocated to biomass. I guess that round wood was not used for biomass production in case a, but it is not clear. ANSWER: 8. As discussed in a previous paper (Valente el al., 2011), "the implementation of forest management as soil scarification and planting can improve the quality of mountain forests, which today is really poor and thus in the long term generates more wood for bioenergy purpose". This explains why we made previously this assumption regarding the assessment of artificial regeneration. In Norway, forest management has generally low intensity and activities in mountain area are scarce, so our study is rich in assumptions.

In the text: "because it can improve the quality of mountain forests, which today is really poor and thus in the long term generates more wood for energy"

Allocation: we add the description of allocation at lines 200-209.
RESULTS
9. Table 1 row 2 - is empty,
ANSWER:9. We deleted row 2

10.What is included under "silviculture" - row 5. In case a preliminary numbers for loading and railway transportation could be included even if they were not calculated ANSWER:10. We added a specification near silvicolture – row 5: soil scarification.
Numbers for loading and railway are already presented in the table for case a.
11.Row 248 - case a logging GWP - 7.3 (not 7.8).
ANSWER:11.The value of 7.8 was replaced by 7.3 kg CO2e
12.Row 254-255 - no number proving the text. ANSWER:12.We added this sentence "As shown in previous calculation (Valente et al. 2012),GWP for diesel train was 0.99 kg CO2e/m3 s.o.b, while GWP for electric train was 0.00001 kg CO2e/m3 s.o.b. Railway transportation had a low GWP per m3 s.o.b., when based on hydroelectric power"
13.Row 259-261 please check the numbers. In case b the GHG is lower, so the save of CO2 should be higher than in case a.

ANSWER:13. We deleted these parts, since we realized that is outside our system boundary, as drawn in the figure. The differences in the numbers are explained by the fact that in the Norwegian case we assume that wood fuels replace oil, coal and natural gas at cogeneration plants, while in the Italian case only at the heating plant.
14.In generally the study conditions are quite different and hardly comparable. So I suggest to use the simulation were it is possible to make the conditions (eg. the transportation distance) more similar or to prove that it is the influence of country. As case studies were done in relatively flat (Norway) and steep (Italy) terrains, it would be useful to know how much area such terrains occupy in these countries and are the same systems used in opposite terrains (in steeper in Norway or in relatively flat in Italy).
ANSWER:14.The fact that conditions are different is an inherent element of any comparison. In mountain areas, Norwegian loggers seem to prefer the harvester-forwarder team rather than a yarder operation (See Lileng 2009).

Lileng, J. Avvirkning med hjulgående maskiner i bratt terreng; Norsk institutt for skog og landskap: 2009; pp 1-7.

We believe that the fact that Italian and Norwegian mountain loggers opt for different technical solutions, apply different silvicultural prescription and face similar (or different) terrain conditions is the main reason why we have a comparison. If they all did the same under the same conditions, there would be no scope for a comparison.
Anyway, a minority of the Norwegian mountain loggers also apply cable yarding (Torgersen, H.; Lisland, T., Excavator-based cable logging and processing system: A Norwegian case study. Int J For Eng 2002, 13, 11-16.). Similarly, a minority of the Italian mountain loggers also apply the harvester-forwarder system (see Spinelli and Magagnotti 2013, reported above).

We added this sentence to the text: "The fact that conditions are different is an inherent element of any comparison. We believe that the choice of different technical solutions for logging operations, the application of different silvicultural prescription, and the presence of different terrain conditions is an inherent element of any comparison. However, we refer to the tables presented in the appendix 1 for specific study conditions"
15. Chapter Discussions
Too wide. A lot of repetitions with information described in other chapters.
Some statements could be in the chapter Results (eg. 337-342). Some statements are not proved (eg. 368-369, 375-377 (all countries?), 404-405 (confirmed by sensitive analysis?) ANSWER: 15.
368-369: This is just the opinion of the authors, and that is why we used the conditional form "might". In the recise manuscript version we have made that clearer by adding the sentence "in our opinions";
375-377: we substituted "other" with "neighbor";
404-405: We deleted "sensitivity analysis"
416-420: we deleted the discussion about bioenergy replacement

We delete also some text according to other comments from reviewer II and III

16. Chapter Conclusions is too wide. Rows 438-440 are not necessary. Leave only important information. ANSWER:16. We removed lines: 438-440; 451-455 (as suggested also by reviewer II); 469-474

REVIEWER II
17. Highlights.
Number 2 is very ambicious. In my opinion, your paper has not enought information for it.
ANSWER 17: We have replaced highlights n. 2, 3 and 4

18. Highlights:
Number 3 very general and ambicious. In my opinion you make a good contribution. However, LCA-Recipe method, for example considers 18 different environmental impact. I mean, more insights are needed.
ANSWER 18.We have replaced highlight n. 2, 3 and 4
Material and methods.

19. The work systems analyzed produce two assortments for each one: logs and residues. How cost and fuel consumption are allocated to them? You should explain it.
ANSWER 19. We added an exthensive description of product allocation at line 200-209
20.What are the conversion factors from machine fuel consumption to emissions? You should indicate.

ANSWER 20. Please, see the tables in the appendix
21. What are the tree species studied? Type of forest? ANSWER 21. That is actually described at lines 160-162:
in both cases vegetation conditions were similar, characterized by coniferous forests, with Norway spruce [Picea abies (L.) Karst.] as the dominant species.
22. Life cycle costing (or Conventional Life cycle costing) is a methodology appropriate to combine with LCA. I suggest you have a look to this reference: Integrating Life Cycle Cost Analysis and LCA, Int J LCA 6 (2) 118, 2001. You have almost all information needed.
ANSWER 22. The authors do not refer to LCC, because in this study they performed a simplified cost accounting, and not a full LCC.
However, the authors are aware of the tentative of integrating LCA and LCC, and therefore they added two references on the subject (Weidima, 2005 and UNEP/SETAC, 2011) and some further word along the text.

For the reviewer:
See the report of Valente et al. 2013 for the differences between LCA and LCC:
Reference: Valente, C., Modahl, I.S., Askham, C. 2013 Method development for Life Cycle Sustainability Assessment (LCSA) of New Norwegian Biorefinery. OR 39.13"
"According to Klöppfer (2008), LCC is the economic counterpart of LCA. As for LCA, LCC is directly linked to the life cycle of a product system for assessing the true costs to be compared with another one having the same function. However, there are substantial differences between LCA and LCC. In economic terms, life cycle is defines as "the sequence product development - production - marketing/sale - end of economic product life". In some cases, the LCA of a product may be longer that the economic life cyle. It is challenging to quantify the costs, especially because it is not easy to calculate the damage that a product can have in the future, and also because some burdens are difficult to describe in monetary terms (e.g. ethical or esthetic burdens). There are substantial differences between LCA and LCC in purpose, activities and flows, unit flows, timing and scope".

23. # According to Material and Methods (line 217), Results (table 1) and conclusions (line 410), Should energy balance be included as another objective (Line 135, 137 and 138)?
ANSWER 23.We added energy use as an objective of the article
24. Content from line 328 to 331 could be moved and added/combined to lines 116 and 117. Similar aspects of Norwegian forest from 2 references.
ANSWER 24. We moved the following text to the introduction:

"In Norway, 49% of forested land has an inclination greater than 20% and most of the potential for increased harvesting is in difficult terrain with low site quality, as is typical of mountain forests"
25. 167 Is more appropriate to indicate than Cradle=Raw Material Extraction, or better, Forest stands? I mean, your system boundary includes forest management.

ANSWER 25. Forest management is included only in case a. Therefore, we inserted “raw material extraction at forest stands”

26. 254 Energy content of assortments is needed. A humidity content percentage should be added.

ANSWER 26.We added this information in the appendix
27. # Lines 258, 259, 260 and 261. Is substitution of fossil at power plant in or out of boundaries study? Line 168 and 169 indicates is out. So, are savings of CO2e before combustion? Anyway, to compare fuel energy content of every raw material (coal, oil, natural gas) should be mention.
ANSWER 27. We realized that replacement was outside our system boundary, and therefore we deleted all results referring to it (see also answer 13 to reviewer 1)
28. Line 267 Where is the sensitivity analysis? I am not able to find it. . I guess some information is missing. There are some results, but more information is needed to understand the results. Mainly if you point out your secondary objective is "to provide empirical evidence of the main uncertainties". If labour cost is an important difference between Norway and Italy, you should explain the percentage of this item in cost items. Furthermore an explanation of the influence of fuel consumption should be added.
ANSWER 28. We added three tables with the results from the sensitivity analyses. We also added this sentence: “chipping and transportation are the most sensitive operations in changes to fuel, because they are the most intensive users of fuel”.

We haven’t done a sensitivity analysis specifically for labor costs for the Norwegian case, but we believe that labor cost is one factor explaning the difference between Norway and Italy.
29. # Line 405. you are considering branches and tree tops, not stems, so It is not clear that increasing tree diameter the result would be different.
ANSWER 29.We deleted the sentence “significant reduction of CO2 emissions can be achieved by increasing the diameter of wood fuel fed into the chipper [61]”
30. #Line 415 If "Energy input was higher in the Norwegian case due to the longer trnsportations distance, you should indicate the distance between forest and terminal. ANSWER 30. 64 km with 46% as load factor, i.e. the distance driven with a full load timber truck per round trip. We added in the text “64 km away”.
31. # Lines from 451 to 456 are not exactly part of your conclusions. I suggest removed these lines.

ANSWER 31. We removed these lines.

REVIEWER III
32. In the abstract you state "The study shows that mountain forests constitute a large potential for fuel biomass in both areas", but this cannot be seen clearly in the text, since there are no figures about this potential, except from those related to the % of mountain forests in each area. Improve the content or remove this sentence. For instance, I don't know if all the potential of logging residues is used in the Italian Alps or not, and therefore it is not possible to know if there is potential or most of it is indeed used.
ANSWER 32. We replaced large potential by “interesting source for fuel biomass”
At line 318 in the discussion we added : “It is to highlight that the actual potential of biomass availability is still underutilized in both countries [42, 43]”.
Italy:
The actual potential is still underutilized (see Zambelli P, Lora C., Spinelli R., Tattoni C., Vitti A., Zatelli P., Ciolli M. A GIS decision support system for regional forest management to assess biomass availability for renewable energy production (2012) Environmental Modelling and Software, 38, pp. 203-213.)
Norway:

Scarlat, Nicolae, Jean-Francois Dallemand, Odd Jarle Skjelhaugen, Dan Asplund, and Lars Nesheim. 2011. "An Overview of the Biomass Resource Potential of Norway for Bioenergy Use." Renewable and Sustainable Energy Reviews 15 (7): 3388–98.
33. Highlights
"We aim to generalize for promoting the use of bioenergy from mountain forests", I think that such highlight is more appropriate for dissemination papers than scientific papers. ANSWER 33. We deleted this highlight
We wrote three new highlights n.2, 3 and 4.
34. Introduction
In lines 52-54, the reference [4] gives the information in way which is not too clear. Considering a forest (or a managed forest) as a system, one gets yearly the amount of biomass that the whole forest is able to produce, but from a portion of the forest. The same is taking place in energy crops, where one gets every three years (for instance) what the crop grows in three years. Therefore, whether the biomass comes form short or long rotation, is not that relevant. In addition to that, you mention in your paper the amount released, while the reference is using a more complicated term, the radiation balance. Stating that natural gas would be preferable in the short term (<20 years) than biomass considering the regrowth of biomass, is something that you should rethink taking also clearer references. ANSWER 34. We deleted lines 52-54.
However, as matter of fact, the carbon stock depends by several factors - not only time horizon, but also harvesting rate, dominant tree species, harvest type, soil type, site preparation techniques, time after disturbance etc. Different forest management practices can affect the C sequestration in the forests in relation to the biomass growth rate and the year of harvest (rotation period) (see e.g. Cherubini et al., 2011). However, in this study we have not focused on the effect of forest management in such detail.
See Marland, G. (2010), Accounting for Carbon Dioxide Emissions from Bioenergy Systems. Journal of Industrial Ecology, 14: 866–869 for the discussion on temporal issue: "A challenge is that some bioenergy systems, especially those involving forest fuels, may result in an increase in greenhouse gas emissions in the short term in return for a decrease in net greenhouse gas emissions in the longer term". This explains why natural gas might be more favorable than bioenergy in the short term.
35. In line 113 you mention that 50% of the domestic consumption of biofuels is used for heat production in households. A mention about the remaining 50% would be helpful for the reader to get an idea of the Norwegian biofuels market.
ANSWER 35. We added "In Norway in 2010, about 53 % of the domestic consumption of wood biofuels for heat production was used in households, 24 % in the pulp and paper production, 11% as wood chips and bark in central district heating, 3% as briquettes and pellets and the remaining 9% in other industries including sawmilling" (Source: Trømborg 2011)
http://www.bioenergytrade.org/downloads/iea-task-40-country-report-2011-norway.pdf).
36. In line 114 you mention the wood pellet market, but what's going on with the wood chip market?

ANSWER 36. We added "At present the Norwegian wood chip market is in decline, partly because of shut downs in the pulp and paper industry, and partly because subsidies for chipping of forest residues have disappeared"
37. In line 115 you mention that the annual increment is more than twice the annual harvest. However, you could be more explicative in line what it is mentioned in a reference mentioned by you: [14]: "the "traditional" concept of sustained-yield forestry, developed in the lowland forests of Europe two centuries ago and applied widely in forests around the world, has been found wanting in many mountain forests"
ANSWER 37. We added this sentence to the text: "around the world, the traditional concept of sustained-yield forestry had to be adapted to the specific conditions of mountain forests, in particular in Norway, to comply with environmental concerns."
38. In line 116 you state that, according to [22], 30% of the forested area is located in the mountains. Please check whether there isn't a newer source of statistics than this one from 2002. Otherwise, you

can state in the text the year this figure is referring. The same could be said for lines 122-123 and source [25], although is newer.
ANSWER 38. We added this sentence "Traditionally, mountain forests have very long cycles, hence we can assume that the forest situation hasn't changed in the last decade in both case studies".

We added the years in the text closed by the references.
39. In line 122, the source [24] is outdated. There is a newer report from ENEA "Verso un'Italia low carbon: sistema energetico, occupazione e investimenti. Scenari e strategie 2013". You should use that, even though the resulting figure is the same. ANSWER 39. We replaced our original reference with the more recent one suggested by the reviewer.
40. In line 124 "In the last three years Italy has increased its bioenergy production". Readers would prefer a period with the initial and ending year, a source, and a figure of this increase. In any case, I believe that Italy has increased the bioenergy production for a longer period. ANSWER 40. We added in the text: "In Italy the number of bioenergy plants is increased from 352 to 419 between 2008 and 2009. During the same period, the total power invested grew from 1555 to 2019 MW".
Reference: "ENAMA, 2011. Studio progetto biomasse. Capitolo 3 censimento impianti, biocarburanti di seconda generazione e casi studio.Ente nazionale per la meccanizzazione agricola. Available from: http://www.enama.it/it/biomasse_studio.php accessed: August 2014

41. In line 132 you state that both case studies occur under similar geomorphological conditions. A table should be provided in Material and Methods for the reader to check that the similarities are in place. However, later on you state that in Norway the case study takes place in a relatively flat area, whereas in Italy it occurs in a steep area: this is not similar from the point of view of geomorphology. Use another term, like "mountain areas" if "geomorphology" is not appropriate.
ANSWER 41. We replaced "geomorphological" with "mountain conditions"
42. Materials and methods
In the materials and methods section I am missing a table comprising some information from both cases: dasometric conditions of forests before and after the harvesting, slopes of the forest or measured area and the type of harvesting/treatment (just stating in the text "steep" or "relatively flat" is clearly insufficient if the aim of the paper is to compare these two systems). You cannot expect the reader to open and print both papers for having access to basic information that you use in your paper. All the information used in this paper should be available in this paper.
ANSWER 42. Please see the answer 14 to reviewer I, (see text at line: 148-152)
For all technical information with refer to the tables in the appendix.

43. Lines 173-175: I agree that m3 s.o.b is a good unit for foresters. However, there is no way in the paper to convert the m3 into energy units, and this is of relevance taking into account that wood density has a huge variability (between species). Since later on you state that for the energy input/output ratio is less than 5%, you could provide the figures for the this calculation. Please consider rewriting the table using MWh as functional unit. In conclusion: the reader should be provided with the figures/formulas you used for energy calculations (net calorific value, etc.). In addition to that, the reader would thank some explanations about how did you achieved to get the results in /m3sob when working with (chipped) logging residues. Did you measured the bulk volume and then multiplied by 0,4? Please explain. Indeed it is a little bit contradictory when you explain that "bark also burns", considering that you are working with logging residues (branches, twigs, needles).

ANSWER 43. In the Italian case we worked with pure Norway spruce, and in Norway the dominant species was also Norway Spruce. Hence, there is no variability in the wood density.

We added the conversion factor for transforming m3 s.o.b. into MWh in the text.

“The conversion factor for transforming m3 loose into m3 s.o.b. is 0.4, while it was 2.12 for transforming m3 s.o.b. into MWh (ÖNORM 1998)”.
In addition a table in appendix reports information about wood density, net calorific value etc.
Regarding chipped logging residues, we have measured the bulk volume and transformed it into solid volume.
For calculating the energy balance the formula is:
The following equation (Ayres, 1978; Hohle, 2010) was used for calculating the energy balance (input-output ratio) of the assortments used for energy production:
IE= Fc x Ec/OE
IE is the energy input ratio and it is calculated in percentage. Fc is the fuel consumption of forest machineries in l/m3 s.o.b., while Ec is the energy content of fuel in kWh divided by OE i.e. the energy output, i.e. the amount of energy released burning wood chips at the combustion plant. The energy output of chips is calculated as the yearly ratio between heat production and wood chip consumption at the plant.
References:
Hohle, A.M.E., 2010. Energy consumption by energy wood supply. OSCAR conference in Forest operations research in the Nordic Baltic Region, October 20-22, 2010, Honne, Norway;
Ayres, R.U., 1978. Resources, environment, and economics: applications of the materials/energy balance principle. New York New York, USA.
44. Line 181: can you make a reference to the attempts done for including social, economic and environmental aspects in LCA?
ANSWER 44.Weidima, B. 2005. “The Integration of Economic and Social Aspects in Life Cycle Impact Assessment.” The International Journal of Life Cycle Assessment 11 (S1) (December 6): 89–96;
UNEP/SETAC, 2011. Towards a Life Cycle Sustainability Assessment: Making Informed Choices on Products. UNEP/SETAC Life Cycle Initiative

Please see answer 22 to reviewer 2.
45. Lines 186-187 and figure 2: please specify that the inputs and outputs you are referring to are the ones of a LCA; otherwise it is confusing. In Figure 2 I am missing the operations "bundling" (case a), felling (case b) and processing (case b). ANSWER 45. In the LCA, the estimated inputs were: the amount of raw materials and fuel consumption. Estimated outputs were: GHG emissions, costs and energy use.

We modified the figure related to system boundary, as suggested.
46. Line 191: "in both cases, the extracted woody biomass was roundwood and logging residues." You should state clearly also that the one used for energy, and subject of this paper, is the biomass "logging residues" (see lines 205-206 and 214) and therefore you apply proper allocation for the LCA. Indeed, any explanation about the allocation of inputs between roundwood and logging residues (silviculture, regeneration and the operation harvesting in case a; operations felling-extraction-processing ain case b) would be appreciated.
ANSWER 46. We added a description of allocation at lines 200-209.
In case study A (paper 1), it was assumed to allocate 70% of emissions into wood fuel production and 30% into timber production, based on a physical causality approach as mass of outputs. Bundling was only allocated to the wood fuel production. For the transportation from the terminal to the combustion plants (paper 2) only wood fuels were transported which made it unnecessary to allocate either the input or the output. Regarding case study B (paper 3), GHG emissions generated from felling and extraction were charged in relation to the total volume of roundwood and logging residues. Later GHG emissions produced by chipping and chip transportation were allocated only to the logging residues component used for energy purpose, while the timber production chain was excluded by the study. At the DHP, emissions were loaded on wood chips from both logging residues and saw mill residues.

47. Lines 198-199: you state that the chain is of the same type. They are completely different, although they aim at using the same type of biomass for energy: logging residues (or tree tops and branches).

ANSWER 47. We replaced “the same chain type” with “the studied chains”.
48. Lines 202-204: if forests are left to natural regeneration, you should also mention that in the discussion, because under the hypothesis of artificial regeneration the associated cost is high, 10.04 EUR/m3 ANSWER 48.Please see answer 8 to reviewer I: we added a sentence regarding why we assumed artificial regeneration at lines 217-218. In addition, in the discussion we added this sentence: “High labor costs explain why the cost for artificial regeneration assumed in case a is so high. This is confirmed by Lindner”.

49. Line 206: the steps are no clear when comparing to the table 1: in table 1 one understands that bundling takes place at the landing. I propose that you consider including bundling within the area of "Logging operations" in table 1 ANSWER 49. We modified table 1 as suggested by the reviewer.
50. Line 211: not system but method (FP0902) (http://www.forestenergy.org/pages/cost-action-fp0902/glossary/?PHPSESSID=75cb0c9631d1cb2b3554d45ef7d86180). Check there that you refer to whole-tree or full-tree. ANSWER 50. We replaced WTS with WTM (whole-tree method)
51. In the table 1:
- be coherent with the amount of significative digits or the amount of decimals
- the second row is empty
- just leaving "Terminal" is not clear. Please use two or three words which are more explicative than just this one ("Transport to terminal", could be clear enough, if I have understood the paper)
ANSWER 51.We modified table 1 as follows:
1) same amount of decimals and digits;
2) deleted row 2
3) “terminal” was replaced by “transport to the terminal”
52. Line 219: how have you assessed the energy released during combustion? Did you use data form the district heating plants about the specific batch? Did you calculate it with net calorific value? In this case, which values of calorific values did you used? All this will be helpful for interpreting table 1 (in case, together with the density or the energy density of the wood of this study.
ANSWER 52. In table 1, we replaced “transport” with “transport to the plant”.
We added in the text the formula for calculating the energy input-output ratio (see comments above). And the sentence “The energy output of chips is calculated as the yearly ratio between heat production and wood chip consumption at the plant”

For specific data, please see the tables in the appendix.
53. Line 227: in these LCA are not included the emissions or the energy inputs for the machines' manufacture? ANSWER 53. No, they are not included. For clarification, we added this sentence: “machine manufacture is not included in the LCA”
54. Line 229 and following: consider a clearer explanation of the sensitivity analysis used.
ANSWER 54. We added this text:
“Sensitivity analysis was carried out to evaluate how changing the input parameter values can influence the results, and to point out the most critical unit processes along the wood fuel supply chain. Fuel consumption was the increased and decreased input parameter for identifying the effects on energy use and GWP respectively. Only in case b, labour cost was the changed input parameter for verifying the impacts on the overall costs. In case a, GHG emissions and costs were increased and decreased one at time for each unit process”.
55. Results
In the results chapter, I am missing a table
showing the results of the sensitivity analysis. Just reading in the text is difficult, and one cannot get a comprehensive idea of the results on that issue.

In addition, if one wants to compare these two systems properly, you could try to produce a table for GWP, cost and energy use for transport, in the different steps where biomass is transported (not within the forest), and related to 1 km (I mean, kgCO2eq/m3sob/km, which you also mention within the paper) so that one can compare a little bit better means of transport and bundle/chips.
ANSWER 55. We added the results of the sensivity analyses in three tables.
Transport distances are added in the text see e.g. 221-223.
56. Line 253: the result is very interesting, but the reader should have the proper calculations or helping figures within the paper. ANSWER 56. We referred to the formula for the energy calculation as presented above in the previous answer 43 to reviewer III.

57. Lines 258-261: presenting the results in kCO2eq/m3sob in this section is useful for comparing against the results shown in Table 1. However, please consider producing the results in kCO2/MWh or other (final, or at least in the silo, priori to burning) energy unit.
ANSWER 57. We have added in the text the conversion factor for transforming m3 s.o.b. into MWh. See also answer 43.
58. Line 264-266: I don't know the rules for compiling case studies, but the reader would thank your effort on producing equivalent data for filling the gap and making a proper comparison.
ANSWER 58. We added three tables with the results from the sensitivity analyses. For further information and comparison, we provided further data in the tables in the appendix.
59. Line 267 onwards: results form the sensitivity analyses . Better if all are shown in a table. The reader doesn't have any reference to what has happened to the 1,5% effect of the 10% variation in the first part of the case a (for instance). ANSWER 59. We added three tables with the results from the sensitivity analyses. For further information and comparison, we have provided all data in the tables in the appendix.
60. Discussion
In line 292 you state that "the Norwegian case shows that logging operations were fully mechanized even in mountain areas." If you describe as relatively flat the area of case a, then case a may not represent a mountain area. In any case, the reader must assume that the case a is representative of mountain areas of Norway. A better link to the following sentence should be done. Maybe, write first "Nowadays…." And then the reference to the case study "and the case study showed that…" (for instance) ANSWER 60:We wrote instead this sentence:
“Nowadays the case study a shows that logging operations were fully mechanized in mountain areas of Hedmark and Oppland”
61. Lines 322-324: you mention that the cost of extraction is 7 EUR/m3 more for the SWS than the WTS (please check if whole-tree or full-tree). However I am missing: 1) reference to the extraction method 2) coherence: you explain this extra cost due to the less efficient motor-manual work, but you are referring to extraction (and not to tree felling and processing) which may involve the same degree of mechanization both for SWS and WTS; please review/clarify.
ANSWER 61. The cost refers to harvesting, and therefore we replaced “cost of extraction” with “harvesting cost”; WTS was replaced with WTM
62. Lines 339-340: you state that "bundling is economically viable for distances longer than 60 km [43] as shown in case a". However, from the data in the paper I cannot see the transport distance between forest and terminal. In addition, I would like to find a justification why bundles are chipped at terminal and not at plant, before railroad transport.
ANSWER 62. Transport distance was added at line 221.
We added this sentence for explaining why chipping is at the terminal/landing:“Norwegian and Italian plants are not equipped with their own chippers and they also have relatively small log yards, due to the need to keep surface area small, because there is relatively little flat land in mountain areas. That explains why chipping is preferably (although not exclusively) performed at a terminal, rather than at the plant.
End use facility chipping system is suitable only for large plants since the investment cost is high. Roadside landing chipping system is suitable also for small plants”

63. Lines 341-342: aren't there boundaries for this "bundling is less energy efficient than not bundling"? I mean, a transport distance of bundles/residues/chips, for instance.
ANSWER 63. We added the sentence: “since it relies on immature technologies”.
The discussion on energy efficiency is more related to the comparison between different forest energy systems in Nordic conditions (in the case of Lindholm, that is Sweden). Currently, the dominant systems for procuring forest biomass in Sweden is comminuting at road side. However, bundling of logging residues showed its potential, but it relied on immature tecnologies, which explains why it is less energy efficient.

64. Line 344: "elsewhere"? [43] Please specify, something like "in Nordic conditions".
ANSWER 64. We deleted the reference and the whole sentence.
We added “bundling...and it incurs an additional cost. This cost should be offset by more efficient transportation, storage and comminution.
Reference: Spinelli, R., Magagnotti, N., Picchi, G., 2012. A supply chain evaluation of slash bundling under the conditions of mountain forestry. Biomass and Bioenergy 36 (2012) 339-345
65. In line 345 you state with a reference a cost of chipping at landing of 3 EUR/m3sob, whereas your result is 10,07. I am missing a discussion, at least a mention, of this huge difference.
ANSWER 65.We deleted this sentence and the reference. We have double checked the reference and we found out that our system and the system studied by Kanzian were based on different assumptions. In Kanzian, e.g. the unproductive time is not included in the study.
66. Line 351-352: you talk about a result of case a, matter of this paper, but the result is not in this paper. You can at least write the figures in this discussion section. ANSWER 66. We added these two sentences (lines 381-383):
a) GWP was 31.4 kg CO_2e/ m3 s.o.b. when wood chips were burned locally [37] compared to the alternative when they were exported to Sweden. In this case, GWP was 22.9 kg CO_2e/ m3 s.o.b.
b) Furthermore, the costs of wood chips for heating is more expensive in Norway (97 NOK/m3 s.o.b.) than in Sweden (63 NOK/m3 s.o.b.).
67. Line 372: check grammar.
ANSWER 67. We added the word “viable”
68. Lines 398-400: you should try to support your statements with sentences
ANSWER 68. We deleted this sentence “The Italian system is limited by poorly developed road and rail infrastructure, which limits the technological and technical choices”.
69. Lines 404-405: please be more explicative why chipping is one of the operations with highest emissions, as confirmed by the sensitivity analysis; 20% savings in fuel consumption would imply 19,8% savings in CO_2 emissions in this operation, meaning that it may be improved. Or can you explain better you idea? ANSWER 69. We can reduce fuel consumption (and therefore emissions) by optimizing chipping, which is obtained by feeding the right material, reducing downtime and timely replacing worn knives, among others”
We added this sentence: “Fuel consumption and therefore emissions can be reduced by optimizing chipping, which is obtained by feeding the right material, reducing downtime and timely replacing worn knives, among others see…” We quoted the following two references among the ones listed below: Spinelli et al., 2014 and Facello et al., 2013.
Please see:

Spinelli R., Glushkov S., Markov I. Managing chipper knife wear to increase chip quality and reduce chipping cost (2014) Biomass and Bioenergy, 62, pp. 117-122.

Facello A., Cavallo E., Magagnotti N., Paletto G., Spinelli R. The effect of knife wear on chip quality and processing cost of chestnut and locust fuel wood (2013) Biomass and Bioenergy, 59, pp. 468-476.

Spinelli R., Magagnotti N. The effect of raw material, cut length, and chip discharge on the performance of an industrial chipper (2012) Forest Products Journal, 62 (7-8), pp. 584-589.

And also:

Spinelli R., Cavallo E., Facello A., Magagnotti N., Nati C., Paletto G. Performance and energy efficiency of alternative comminution principles: Chipping versus grinding (2012) Scandinavian Journal of Forest Research, 27 (4), pp. 393-400.

Spinelli R., Magagnotti N., Paletto G., Preti C. Determining the impact of some wood characteristics on the performance of a mobile chipper (2011) Silva Fennica, 45 (1), pp. 85-95.

“As shown in the sensitivity analysis” was deleted
70. Line 411: same as before regarding the calculation of the input/output ratio. The calculation figures should be within the paper.
ANSWER 70. We added the formula in the text.Please see the answer 43 to reviewer III above
71. Line 428: "chain" is repeated
ANSWER 71. We deleted “chain”
72. Conclusions
Lines 456-458: you state that fuel consumption is a critical parameter in GHG emissions from truck transportation and chipping, but in the paper there are only the figures (written within the text) for chipping in Italy.
ANSWER 72. We provided the tables showing the results from the sensitivity analyses for both cases. An explanation is provided in the discussion.
73. Lines 459-461: "the integration of logging residue harvesting with the conventional logging of round wood improved the efficiency of the supply chains". I might have read the paper too quickly, but I don't remember to have seen this analysed in this paper. A table in the discussion, or figures, should be needed. If you refer to the data about SWS in Italy, I think it is not enough. ANSWER 73.We deleted this sentence
74. Lines 467-468: this is an interesting thought. However, I think that forest management, regardless of its objective (bioenergy production, leisure, wood production, etc.) must always be sustainable socioeconomically and environmentally ANSWER 74. We agree with the reviewer on the fact that forest management should always be sustainable.

Cover letter

I am writing to submit the revised version of the manuscript entitled, “Mountain forests wood fuel supply chains: comparative studies between Norway and Italy” for potential publication in Biomass and Bioenergy.

Thank you for receiving our manuscript again and considering it for publication. We appreciate your time and look forward to your response.

Kind regards,

Clara Valente and co-authors

***Detailed Response to Reviewers**

REVIEWER 1	
1. Chapter Introduction is too long, some parts are obvious knowledge (eg. rows 43-53) or have little connection with the aims of the article (eg. 89-91). I would suggest to authors to look through this chapter again and to leave only those parts which really are important for this article.	ANSWER 1. The authors have deleted these lines: a) from 45 to 54, since they refer to general knowledge about fossil fuels as net contributors of CO_2. b) from 89 to 91, because they contain general information about the functionality of mountain forests c) from 95 to 97, because they refer to general knowledge on climate modelling.
2. 118 row. It is really truth that in all cases clear cuttings are forbidden in mountain forests in Norway and in Italy? Reviewer has visited some sites in Norway that were clear cut.	ANSWER 2. Italy: Italian silviculture is largely based on continuous cover forestry (CCF) and applies selection cutting as the main prescription (Spinelli and Magagnotti 2013). Clearcuts are only applied to coppice forests, on relatively small areas (<5-10 ha, depending on regional regulations). No clearcuts larger than 0.5 ha are allowed on high forests, with the exception of salvage cuts, whose extension depends on the surface area actually damaged. In the introduction we added the following text: "Italian silviculture is largely based on continuous cover forestry (CCF) and applies selection cutting as the main prescription (Spinelli and Magagnotti 2013). No clearcuts larger than 0.5 ha are allowed on high forests, with the exception of salvage cuts". *Reference:* Spinelli, R., Magagnotti, N. (2013) The effect of harvest tree distribution on harvesting productivity in selection cuts, Scandinavian Journal of Forest Research, 28:7, 701-709 Norway: mountain forest are harvested through small clear cuts. 5-10 trees should be left per ha in the felling areas (page 44: forest management guidelines European forest institute). According to the Standard for sustainable forest management: "The harvesting methods for spruce must as far as possible follow the "mountain forest selection cutting system". Small-scale clear-cutting and smaller seed tree stand felling should be used as far as possible to promote regeneration in the pine forest". Specific rules and environmental restrictions

	characterize the management of these Norwegian forest stands. In the revise manuscript version we added the following text: “ Selective cutting and small-scale clear cutting or group cutting, clear cutting of areas from 0.2 to 0.5 ha, are the conventional harvesting systems for mountain conditions”
3. The study objects (131-135) could be described in Chapter 2.	ANSWER 3. Moved to chapter 2
4. Chapter Material and Methods I want to ask the authors to describe more clearly the study objects and under what conditions the study results were obtained. The case studies were done under different conditions, production systems, so it very important to know what was the logging, chipping, and transportation conditions, what machines were used, what salaries where used in calculations and so on. Are these chip production systems usual in case of Italy and Norway?	ANSWER: 4. Italy: The system described is quite typical for the Italian Alps, and in general of modern day Alpine logging (Spinelli et al. 2007). *Reference:* Spinelli, R., Nati, C., Magagnotti, N. Recovering logging residue: Experiences from the Italian Eastern Alps. (2007) Croatian Journal of Forest Engineering, 28 (1), pp. 1-9. Norway: harvester and forwarder are tipically used in logging operations in Norway. Forest residues are usually left at the stand, but in our case study we assume them to be bundled. Transport to Sweden usually occurs by train as assumed in or case study. *We added in the revised text*: “The object of this study is to compare two real-life examples of forest fuel supply chains in two mountainous countries, Norway -Hedmark/Oppland counties (case a)- and Italy -Fiemme Valley (case b). In the text, the terms “Norwegian case” and “Italian case” indicate generically these two regions. The system described is quite typical for the Italian Alps, and in general of modern day Alpine logging (Spinelli et al. 2007), while the Norwegian system represents common praxis among theoretical elements. At the same time, these case studies offer contrasting economic and cultural environments, as expected for northern and southern Europe, respectively”. Regarding chip production system, please look at the answer 62 to reviewer III below (chipping at the landing/terminal versus chipping at the plant). For more information, please refer to appendix 1.
5. 156 row. What is relatively flat? Steep?	ANSWER:5. Definition of flat terrain: “the eastern region of Norway, Hedmark and

	Oppland are characterized by mostly high plateaus located at high altitude, but characterized by minimum slope. Differently it is the situation on the western coast where the forests are located in steep terrains surrounded by fjords” Definition of steep terrain in Italy: There is not a standard definition for steep terrain, but we can refer to terrains of the third class of Hippoliti, having a slope >40%. In the text: “having a slope > 40% according to Hippoliti classification” Reference: Hippoliti G. 1983. Appunti di Meccanizzazione forestale. Ed. Università di Firenze. Facoltà di Agraria. Firenze (Italia).
6. I would recommend removing all discussions from this sector (eg. Rows 147-153, 164-172), and describe very clearly the methods (only once one method) which was used in this study	ANSWER:6. The authors have deleted lines 147-153 and lines 164-172, because they agree with the need for reducing the length of the article and because these lines provide generic information. For the methodology we refer to lines 140-152.
7. 176-179 rows. I would prefer that in scientific papers the things would be named as they are. Nor climate change neither GWP were measured in this study, but only GHG.	ANSWER:7. The characerization model for GHG emissions is GWP. This is a terminology accepted by the scientific commmunity and very common in LCA studies.
8. 202-204 rows. Why artificial regeneration was evaluated in case a, if the authors declare that natural regeneration was more common in Norway. (I guess that statistics about regeneration method should exists)/ There is no explanations how regeneration costs and GHG was allocated to biomass. I guess that round wood was not used for biomass production in case a, but it is not clear.	ANSWER: 8. As discussed in a previous paper (Valente el al., 2011), “the implementation of forest management as soil scarification and planting can improve the quality of mountain forests, which today is really poor and thus in the long term generates more wood for bioenergy purpose”. This explains why we made previously this assumption regarding the assessment of artificial regeneration. In Norway, forest management has generally low intensity and activities in mountain area are scarce, so our study is rich in assumptions. In the text: “because it can improve the quality of mountain forests, which today is really poor and thus in the long term generates more wood for energy” Allocation: we add the description of allocation at lines 200-209.
RESULTS	
9. Table 1 row 2 - is empty,	ANSWER:9. We deleted row 2

10.What is included under "silviculture" - row 5. In case a preliminary numbers for loading and railway transportation could be included even if they were not calculated	ANSWER:10. We added a specification near silvicolture – row 5: soil scarification. Numbers for loading and railway are already presented in the table for case a.
11.Row 248 - case a logging GWP - 7.3 (not 7.8).	ANSWER:11.The value of 7.8 was replaced by 7.3 kg CO2e
12.Row 254-255 - no number proving the text.	ANSWER:12.We added this sentence "As shown in previous calculation (Valente et al. 2012),GWP for diesel train was 0.99 kg CO2e/m3 s.o.b, while GWP for electric train was 0.00001 kg CO2e/m3 s.o.b. Railway transportation had a low GWP per m3 s.o.b., when based on hydroelectric power"
13.Row 259-261 please check the numbers. In case b the GHG is lower, so the save of CO2 should be higher than in case a.	ANSWER:13. We deleted these parts, since we realized that is outside our system boundary, as drawn in the figure. The differences in the numbers are explained by the fact that in the Norwegian case we assume that wood fuels replace oil, coal and natural gas at cogeneration plants, while in the Italian case only at the heating plant.
14.In generally the study conditions are quite different and hardly comparable. So I suggest to use the simulation were it is possible to make the conditions (eg. the transportation distance) more similar or to prove that it is the influence of country. As case studies were done in relatively flat (Norway) and steep (Italy) terrains, it would be useful to know how much area such terrains occupy in these countries and are the same systems used in opposite terrains (in steeper in Norway or in relatively flat in Italy).	ANSWER:14.The fact that conditions are different is an inherent element of any comparison. In mountain areas, Norwegian loggers seem to prefer the harvester-forwarder team rather than a yarder operation (See Lileng 2009). Lileng, J. Avvirkning med hjulgående maskiner i bratt terreng; Norsk institutt for skog og landskap: 2009; pp 1-7. We believe that the fact that Italian and Norwegian mountain loggers opt for different technical solutions, apply different silvicultural prescription and face similar (or different) terrain conditions is the main reason why we have a comparison. If they all did the same under the same conditions, there would be no scope for a comparison. Anyway, a minority of the Norwegian mountain loggers also apply cable yarding (Torgersen, H.; Lisland, T., Excavator-based cable logging and processing system: A Norwegian case study. Int J For Eng 2002, 13, 11-16.). Similarly, a minority of the Italian mountain loggers also apply the harvester-forwarder system (see Spinelli and Magagnotti 2013, reported above). We added this sentence to the text: "The fact that

	conditions are different is an inherent element of any comparison. We believe that the choice of different technical solutions for logging operations, the application of different silvicultural prescription, and the presence of different terrain conditions is an inherent element of any comparison. However, we refer to the tables presented in the appendix 1 for specific study conditions”
15. Chapter Discussions Too wide. A lot of repetitions with information described in other chapters. Some statements could be in the chapter Results (eg. 337-342). Some statements are not proved (eg. 368-369, 375-377 (all countries?), 404-405 (confirmed by sensitive analysis?)	ANSWER: 15. 368-369: This is just the opinion of the authors, and that is why we used the conditional form “might”. In the recise manuscript version we have made that clearer by adding the sentence “in our opinions”; 375-377: we substituted “other” with ”neighbor”; 404-405: We deleted “sensitivity analysis” 416-420: we deleted the discussion about bioenergy replacement We delete also some text according to other comments from reviewer II and III
16. Chapter Conclusions is too wide. Rows 438-440 are not necessary. Leave only important information.	ANSWER:16. We removed lines: 438-440; 451-455 (as suggested also by reviewer II); 469-474

REVIEWER II

17. Highlights. Number 2 is very ambicious. In my opinion, your paper has not enought information for it.	ANSWER 17: We have replaced highlights n. 2, 3 and 4
18. Highlights: Number 3 very general and ambicious. In my opinion you make a good contribution. However, LCA-Recipe method, for example considers 18 different environmental impact. I mean, more insights are needed.	ANSWER 18.We have replaced highlight n. 2, 3 and 4
Material and methods.	
19. The work systems analyzed produce two assortments for each one: logs and residues. How cost and fuel consumption are allocated to them? You should explain it.	ANSWER 19. We added an exthensive description of product allocation at line 200-209
20.What are the conversion factors from machine fuel consumption to emissions? You should indicate.	ANSWER 20. Please, see the tables in the appendix

21. What are the tree species studied? Type of forest?	ANSWER 21. That is actually described at lines 160-162: in both cases vegetation conditions were similar, characterized by coniferous forests, with Norway spruce [Picea abies (L.) Karst.] as the dominant species.
22. Life cycle costing (or Conventional Life cycle costing) is a methodology appropriate to combine with LCA. I suggest you have a look to this reference: Integrating Life Cycle Cost Analysis and LCA, Int J LCA 6 (2) 118, 2001. You have almost all information needed.	ANSWER 22. The authors do not refer to LCC, because in this study they performed a simplified cost accounting, and not a full LCC. However, the authors are aware of the tentative of integrating LCA and LCC, and therefore they added two references on the subject (Weidima, 2005 and UNEP/SETAC, 2011) and some further word along the text. For the reviewer: See the report of Valente et al. 2013 for the differences between LCA and LCC: Reference: Valente, C., Modahl, I.S., Askham, C. 2013 Method development for Life Cycle Sustainability Assessment (LCSA) of New Norwegian Biorefinery. OR 39.13" "According to Klöppfer (2008), LCC is the economic counterpart of LCA. As for LCA, LCC is directly linked to the life cycle of a product system for assessing the true costs to be compared with another one having the same function. However, there are substantial differences between LCA and LCC. In economic terms, life cycle is defines as "the sequence product development - production - marketing/sale - end of economic product life". In some cases, the LCA of a product may be longer that the economic life cyle. It is challenging to quantify the costs, especially because it is not easy to calculate the damage that a product can have in the future, and also because some burdens are difficult to describe in monetary terms (e.g. ethical or esthetic burdens). There are substantial differences between LCA and LCC in purpose, activities and flows, unit flows, timing and scope".
23. # According to Material and Methods (line 217), Results (table 1) and conclusions (line 410), Should energy balance be included as another objective (Line 135, 137 and 138)?	ANSWER 23.We added energy use as an objective of the article
24. Content from line 328 to 331 could be moved and added/combined to lines 116 and 117. Similar aspects of Norwegian forest from 2 references.	ANSWER 24. We moved the following text to the introduction: "In Norway, 49% of forested land has an

	inclination greater than 20% and most of the potential for increased harvesting is in difficult terrain with low site quality, as is typical of mountain forests”
25. 167 Is more appropriate to indicate than Cradle=Raw Material Extraction, or better, Forest stands? I mean, your system boundary includes forest management.	ANSWER 25. Forest management is included only in case a. Therefore, we inserted “raw material extraction at forest stands”
26. 254 Energy content of assortments is needed. A humidity content percentage should be added.	ANSWER 26.We added this information in the appendix
27. # Lines 258, 259, 260 and 261. Is substitution of fossil at power plant in or out of boundaries study? Line 168 and 169 indicates is out. So, are savings of CO2e before combustion? Anyway, to compare fuel energy content of every raw material (coal, oil, natural gas) should be mention.	ANSWER 27. We realized that replacement was outside our system boundary, and therefore we deleted all results referring to it (see also answer 13 to reviewer 1)
28. Line 267 Where is the sensitivity analysis? I am not able to find it. . I guess some information is missing. There are some results, but more information is needed to understand the results. Mainly if you point out your secondary objective is "to provide empirical evidence of the main uncertainties". If labour cost is an important difference between Norway and Italy, you should explain the percentage of this item in cost items. Furthermore an explanation of the influence of fuel consumption should be added.	ANSWER 28. We added three tables with the results from the sensitivity analyses. We also added this sentence: “chipping and transportation are the most sensitive operations in changes to fuel, because they are the most intensive users of fuel”. We haven’t done a sensitivity analysis specifically for labor costs for the Norwegian case, but we believe that labor cost is one factor explaning the difference between Norway and Italy.
29. # Line 405. you are considering branches and tree tops, not stems, so It is not clear that increasing tree diameter the result would be different.	ANSWER 29.We deleted the sentence “significant reduction of CO_2 emissions can be achieved by increasing the diameter of wood fuel fed into the chipper [61]”
30. #Line 415 If "Energy input was higher in the Norwegian case due to the longer trnsportations distance, you should indicate the distance between forest and terminal.	ANSWER 30. 64 km with 46% as load factor, i.e. the distance driven with a full load timber truck per round trip. We added in the text “64 km away”.
31. # Lines from 451 to 456 are not exactly part of your conclusions. I suggest removed these lines.	ANSWER 31. We removed these lines.

REVIEWER III

32. In the **abstract** you state "The study shows that mountain forests constitute a large potential for fuel biomass in both areas", but this cannot be seen clearly in the text, since there are no figures about this potential, except from those related to the % of mountain forests in each area.	ANSWER 32. We replaced large potential by “interesting source for fuel biomass” At line 318 in the discussion we added : “It is to highlight that the actual potential of biomass availability is still underutilized in both countries [42, 43]”.

Improve the content or remove this sentence. For instance, I don't know if all the potential of logging residues is used in the Italian Alps or not, and therefore it is not possible to know if there is potential or most of it is indeed used.	***Italy:*** The actual potential is still underutilized (see Zambelli P, Lora C., Spinelli R., Tattoni C., Vitti A., Zatelli P., Ciolli M. A GIS decision support system for regional forest management to assess biomass availability for renewable energy production (2012) Environmental Modelling and Software, 38, pp. 203-213.) **Norway:** Scarlat, Nicolae, Jean-Francois Dallemand, Odd Jarle Skjelhaugen, Dan Asplund, and Lars Nesheim. 2011. "An Overview of the Biomass Resource Potential of Norway for Bioenergy Use." Renewable and Sustainable Energy Reviews 15 (7): 3388–98.
33. Highlights "We aim to generalize for promoting the use of bioenergy from mountain forests", I think that such highlight is more appropriate for dissemination papers than scientific papers.	ANSWER 33. We deleted this highlight We wrote three new highlights n.2, 3 and 4.
34. Introduction In lines 52-54, the reference [4] gives the information in way which is not too clear. Considering a forest (or a managed forest) as a system, one gets yearly the amount of biomass that the whole forest is able to produce, but from a portion of the forest. The same is taking place in energy crops, where one gets every three years (for instance) what the crop grows in three years. Therefore, whether the biomass comes form short or long rotation, is not that relevant. In addition to that, you mention in your paper the amount released, while the reference is using a more complicated term, the radiation balance. Stating that natural gas would be preferable in the short term (<20 years) than biomass considering the regrowth of biomass, is something that you should rethink taking also clearer references.	ANSWER 34. We deleted lines 52-54. However, as matter of fact, the carbon stock depends by several factors - not only time horizon, but also harvesting rate, dominant tree species, harvest type, soil type, site preparation techniques, time after disturbance etc. Different forest management practices can affect the C sequestration in the forests in relation to the biomass growth rate and the year of harvest (rotation period) (see e.g. Cherubini et al., 2011). However, in this study we have not focused on the effect of forest management in such detail. See Marland, G. (2010), Accounting for Carbon Dioxide Emissions from Bioenergy Systems. Journal of Industrial Ecology, 14: 866–869 for the discussion on temporal issue: "A challenge is that some bioenergy systems, especially those involving forest fuels, may result in an increase in greenhouse gas emissions in the short term in return for a decrease in net greenhouse gas emissions in the longer term". This explains why natural gas might be more favorable than bioenergy in the short term.
35. In line 113 you mention that 50% of the domestic consumption of biofuels is used for heat production in households. A mention about the remaining 50% would be helpful for the reader to get an idea of the Norwegian biofuels market.	ANSWER 35. We added "In Norway in 2010, about 53 % of the domestic consumption of wood biofuels for heat production was used in households, 24 % in the pulp and paper production, 11% as wood chips and bark in central district heating, 3% as briquettes and pellets and the remaining 9% in other

	industries including sawmilling" (Source: Trømborg 2011) http://www.bioenergytrade.org/downloads/iea-task-40-country-report-2011-norway.pdf).
36. In line 114 you mention the wood pellet market, but what's going on with the wood chip market?	ANSWER 36. We added "At present the Norwegian wood chip market is in decline, partly because of shut downs in the pulp and paper industry, and partly because subsidies for chipping of forest residues have disappeared"
37. In line 115 you mention that the annual increment is more than twice the annual harvest. However, you could be more explicative in line what it is mentioned in a reference mentioned by you: [14]: "the "traditional" concept of sustained-yield forestry, developed in the lowland forests of Europe two centuries ago and applied widely in forests around the world, has been found wanting in many mountain forests"	ANSWER 37. We added this sentence to the text: "around the world, the traditional concept of sustained-yield forestry had to be adapted to the specific conditions of mountain forests, in particular in Norway, to comply with environmental concerns."
38. In line 116 you state that, according to [22], 30% of the forested area is located in the mountains. Please check whether there isn't a newer source of statistics than this one from 2002. Otherwise, you can state in the text the year this figure is referring. The same could be said for lines 122-123 and source [25], although is newer.	ANSWER 38. We added this sentence "Traditionally, mountain forests have very long cycles, hence we can assume that the forest situation hasn't changed in the last decade in both case studies". We added the years in the text closed by the references.
39. In line 122, the source [24] is outdated. There is a newer report from ENEA "Verso un'Italia low carbon: sistema energetico, occupazione e investimenti. Scenari e strategie 2013". You should use that, even though the resulting figure is the same.	ANSWER 39. We replaced our original reference with the more recent one suggested by the reviewer.
40. In line 124 "In the last three years Italy has increased its bioenergy production". Readers would prefer a period with the initial and ending year, a source, and a figure of this increase. In any case, I believe that Italy has increased the bioenergy production for a longer period.	ANSWER 40. We added in the text: "In Italy the number of bioenergy plants is increased from 352 to 419 between 2008 and 2009. During the same period, the total power invested grew from 1555 to 2019 MW". Reference: "ENAMA, 2011. Studio progetto biomasse. Capitolo 3 censimento impianti, biocarburanti di seconda generazione e casi studio.Ente nazionale per la meccanizzazione agricola. Available from: http://www.enama.it/it/biomasse_studio.php accessed: August 2014
41. In line 132 you state that both case studies occur under similar geomorphological conditions. A table should be provided in Material and Methods for the reader to check	ANSWER 41. We replaced "geomorphological" with "mountain conditions"

that the similarities are in place. However, later on you state that in Norway the case study takes place in a relatively flat area, whereas in Italy it occurs in a steep area: this is not similar from the point of view of geomorphology. Use another term, like "mountain areas" if "geomorphology" is not appropriate.	
42. Materials and methods In the materials and methods section I am missing a table comprising some information from both cases: dasometric conditions of forests before and after the harvesting, slopes of the forest or measured area and the type of harvesting/treatment (just stating in the text "steep" or "relatively flat" is clearly insufficient if the aim of the paper is to compare these two systems). You cannot expect the reader to open and print both papers for having access to basic information that you use in your paper. All the information used in this paper should be available in this paper.	ANSWER 42. Please see the answer 14 to reviewer I, (see text at line: 148-152) For all technical information with refer to the tables in the appendix.
43. Lines 173-175: I agree that m3 s.o.b is a good unit for foresters. However, there is no way in the paper to convert the m3 into energy units, and this is of relevance taking into account that wood density has a huge variability (between species). Since later on you state that for the energy input/output ratio is less than 5%, you could provide the figures for the this calculation. Please consider rewriting the table using MWh as functional unit. In conclusion: the reader should be provided with the figures/formulas you used for energy calculations (net calorific value, etc.). In addition to that, the reader would thank some explanations about how did you achieved to get the results in /m3sob when working with (chipped) logging residues. Did you measured the bulk volume and then multiplied by 0,4? Please explain. Indeed it is a little bit contradictory when you explain that "bark also burns", considering that you are working with logging residues (branches, twigs, needles).	ANSWER 43. In the Italian case we worked with pure Norway spruce, and in Norway the dominant species was also Norway Spruce. Hence, there is no variability in the wood density. We added the conversion factor for transforming m3 s.o.b. into MWh in the text. “The conversion factor for transforming m3 loose into m3 s.o.b. is 0.4, while it was 2.12 for transforming m3 s.o.b. into MWh (ÖNORM 1998)”. In addition a table in appendix reports information about wood density, net calorific value etc. Regarding chipped logging residues, we have measured the bulk volume and transformed it into solid volume. For calculating the energy balance the formula is: The following equation (Ayres, 1978; Hohle, 2010) was used for calculating the energy balance (input- output ratio) of the assortments used for energy production: IE= Fc x Ec/OE IE is the energy input ratio and it is calculated in percentage. Fc is the fuel consumption of forest machineries in l/m3 s.o.b., while Ec is the energy content of fuel in kWh divided by OE i.e. the energy output, i.e. the amount of energy

	released burning wood chips at the combustion plant. The energy output of chips is calculated as the yearly ratio between heat production and wood chip consumption at the plant. References: Hohle, A.M.E., 2010. Energy consumption by energy wood supply. OSCAR conference in Forest operations research in the Nordic Baltic Region, October 20-22, 2010, Honne, Norway; Ayres, R.U., 1978. Resources, environment, and economics: applications of the materials/energy balance principle. New York New York, USA.
44. Line 181: can you make a reference to the attempts done for including social, economic and environmental aspects in LCA?	ANSWER 44.Weidima, B. 2005. “The Integration of Economic and Social Aspects in Life Cycle Impact Assessment.” The International Journal of Life Cycle Assessment 11 (S1) (December 6): 89–96; UNEP/SETAC, 2011. Towards a Life Cycle Sustainability Assessment: Making Informed Choices on Products. UNEP/SETAC Life Cycle Initiative Please see answer 22 to reviewer 2.
45. Lines 186-187 and figure 2: please specify that the inputs and outputs you are referring to are the ones of a LCA; otherwise it is confusing. In Figure 2 I am missing the operations "bundling" (case a), felling (case b) and processing (case b).	ANSWER 45. In the LCA, the estimated inputs were: the amount of raw materials and fuel consumption. Estimated outputs were: GHG emissions, costs and energy use. We modified the figure related to system boundary, as suggested.
46. Line 191: "in both cases, the extracted woody biomass was roundwood and logging residues." You should state clearly also that the one used for energy, and subject of this paper, is the biomass "logging residues" (see lines 205-206 and 214) and therefore you apply proper allocation for the LCA. Indeed, any explanation about the allocation of inputs between roundwood and logging residues (silviculture, regeneration and the operation harvesting in case a; operations felling-extraction-processing ain case b) would be appreciated.	ANSWER 46. We added a description of allocation at lines 200-209. In case study A (paper 1), it was assumed to allocate 70% of emissions into wood fuel production and 30% into timber production, based on a physical causality approach as mass of outputs. Bundling was only allocated to the wood fuel production. For the transportation from the terminal to the combustion plants (paper 2) only wood fuels were transported which made it unnecessary to allocate either the input or the output. Regarding case study B (paper 3), GHG emissions generated from felling and extraction were charged in relation to the total volume of roundwood and logging residues. Later GHG emissions produced by chipping and chip transportation were allocated only to the logging residues component used for energy purpose, while the timber production chain was excluded by the study. At the DHP, emissions were loaded on wood chips from both

	logging residues and saw mill residues.
47. Lines 198-199: you state that the chain is of the same type. They are completely different, although they aim at using the same type of biomass for energy: logging residues (or tree tops and branches).	ANSWER 47. We replaced “the same chain type” with “the studied chains”.
48. Lines 202-204: if forests are left to natural regeneration, you should also mention that in the discussion, because under the hypothesis of artificial regeneration the associated cost is high, 10.04 EUR/m3	ANSWER 48.Please see answer 8 to reviewer I: we added a sentence regarding why we assumed artificial regeneration at lines 217-218. In addition, in the discussion we added this sentence: “High labor costs explain why the cost for artificial regeneration assumed in case a is so high. This is confirmed by Lindner”.
49. Line 206: the steps are no clear when comparing to the table 1: in table 1 one understands that bundling takes place at the landing. I propose that you consider including bundling within the area of "Logging operations" in table 1	ANSWER 49. We modified table 1 as suggested by the reviewer.
50. Line 211: not system but method (FP0902) (http://www.forestenergy.org/pages/cost-action-fp0902/glossary/?PHPSESSID=75cb0c9631d1cb2b3554d45ef7d86180). Check there that you refer to whole-tree or full-tree.	ANSWER 50. We replaced WTS with WTM (whole-tree method)
51. In the table 1: - be coherent with the amount of significative digits or the amount of decimals - the second row is empty - just leaving "Terminal" is not clear. Please use two or three words which are more explicative than just this one ("Transport to terminal", could be clear enough, if I have understood the paper)	ANSWER 51.We modified table 1 as follows: 1) same amount of decimals and digits; 2) deleted row 2 3) “terminal” was replaced by “transport to the terminal”
52. Line 219: how have you assessed the energy released during combustion? Did you use data form the district heating plants about the specific batch? Did you calculate it with net calorific value? In this case, which values of calorific values did you used? All this will be helpful for interpreting table 1 (in case, together with the density or the energy density of the wood of this study.	ANSWER 52. In table 1, we replaced “transport” with “transport to the plant”. We added in the text the formula for calculating the energy input-output ratio (see comments above). And the sentence “The energy output of chips is calculated as the yearly ratio between heat production and wood chip consumption at the plant” For specific data, please see the tables in the appendix.
53. Line 227: in these LCA are not included the emissions or the energy inputs for the machines'	ANSWER 53. No, they are not included. For clarification, we added this sentence: “machine

manufacture?	manufacture is not included in the LCA"
54. Line 229 and following: consider a clearer explanation of the sensitivity analysis used.	ANSWER 54. We added this text: "Sensitivity analysis was carried out to evaluate how changing the input parameter values can influence the results, and to point out the most critical unit processes along the wood fuel supply chain. Fuel consumption was the increased and decreased input parameter for identifying the effects on energy use and GWP respectively. Only in case b, labour cost was the changed input parameter for verifying the impacts on the overall costs. In case a, GHG emissions and costs were increased and decreased one at time for each unit process".
55. Results In the results chapter, I am missing a table showing the results of the sensitivity analysis. Just reading in the text is difficult, and one cannot get a comprehensive idea of the results on that issue. In addition, if one wants to compare these two systems properly, you could try to produce a table for GWP, cost and energy use for transport, in the different steps where biomass is transported (not within the forest), and related to 1 km (I mean, kgCO2eq/m3sob/km, which you also mention within the paper) so that one can compare a little bit better means of transport and bundle/chips.	ANSWER 55. We added the results of the sensivity analyses in three tables. Transport distances are added in the text see e.g. 221-223.
56. Line 253: the result is very interesting, but the reader should have the proper calculations or helping figures within the paper.	ANSWER 56. We referred to the formula for the energy calculation as presented above in the previous answer 43 to reviewer III.
57. Lines 258-261: presenting the results in kCO2eq/m3sob in this section is useful for comparing against the results shown in Table 1. However, please consider producing the results in kCO2/MWh or other (final, or at least in the silo, priori to burning) energy unit.	ANSWER 57. We have added in the text the conversion factor for transforming m3 s.o.b. into MWh. See also answer 43.
58. Line 264-266: I don't know the rules for compiling case studies, but the reader would thank your effort on producing equivalent data for filling the gap and making a proper comparison.	ANSWER 58. We added three tables with the results from the sensitivity analyses. For further information and comparison, we provided further data in the tables in the appendix.
59. Line 267 onwards: results form the sensitivity analyses . Better if all are shown in a table. The reader doesn't have any reference to what has happened to the 1,5% effect of the 10% variation in the first part of the case a (for	ANSWER 59. We added three tables with the results from the sensitivity analyses. For further information and comparison, we have provided all data in the tables in the appendix.

instance).	
60. Discussion In line 292 you state that "the Norwegian case shows that logging operations were fully mechanized even in mountain areas." If you describe as relatively flat the area of case a, then case a may not represent a mountain area. In any case, the reader must assume that the case a is representative of mountain areas of Norway. A better link to the following sentence should be done. Maybe, write first "Nowadays…." And then the reference to the case study "and the case study showed that…" (for instance)	ANSWER 60:We wrote instead this sentence: "Nowadays the case study a shows that logging operations were fully mechanized in mountain areas of Hedmark and Oppland"
61. Lines 322-324: you mention that the cost of extraction is 7 EUR/m3 more for the SWS than the WTS (please check if whole-tree or full-tree). However I am missing: 1) reference to the extraction method 2) coherence: you explain this extra cost due to the less efficient motor-manual work, but you are referring to extraction (and not to tree felling and processing) which may involve the same degree of mechanization both for SWS and WTS; please review/clarify.	ANSWER 61. The cost refers to harvesting, and therefore we replaced "cost of extraction" with "harvesting cost"; WTS was replaced with WTM
62. Lines 339-340: you state that "bundling is economically viable for distances longer than 60 km [43] as shown in case a". However, from the data in the paper I cannot see the transport distance between forest and terminal. In addition, I would like to find a justification why bundles are chipped at terminal and not at plant, before railroad transport.	ANSWER 62. Transport distance was added at line 221. We added this sentence for explaining why chipping is at the terminal/landing:"Norwegian and Italian plants are not equipped with their own chippers and they also have relatively small log yards, due to the need to keep surface area small, because there is relatively little flat land in mountain areas. That explains why chipping is preferably (although not exclusively) performed at a terminal, rather than at the plant. End use facility chipping system is suitable only for large plants since the investment cost is high. Roadside landing chipping system is suitable also for small plants"
63. Lines 341-342: aren't there boundaries for this "bundling is less energy efficient than not bundling"? I mean, a transport distance of bundles/residues/chips, for instance.	ANSWER 63. We added the sentence: "since it relies on immature technologies". The discussion on energy efficiency is more related to the comparison between different forest energy systems in Nordic conditions (in the case of Lindholm, that is Sweden). Currently, the dominant systems for procuring forest biomass in Sweden is comminuting at road side. However, bundling of logging residues showed its potential, but it relied on immature tecnologies, which explains why it is less energy efficient.

64. Line 344: "elsewhere"? [43] Please specify, something like "in Nordic conditions".	ANSWER 64. We deleted the reference and the whole sentence. We added “bundling...and it incurs an additional cost. This cost should be offset by more efficient transportation, storage and comminution. Reference: Spinelli, R., Magagnotti, N., Picchi, G., 2012. A supply chain evaluation of slash bundling under the conditions of mountain forestry. Biomass and Bioenergy 36 (2012) 339-345
65. In line 345 you state with a reference a cost of chipping at landing of 3 EUR/m3sob, whereas your result is 10,07. I am missing a discussion, at least a mention, of this huge difference.	ANSWER 65.We deleted this sentence and the reference. We have double checked the reference and we found out that our system and the system studied by Kanzian were based on different assumptions. In Kanzian, e.g. the unproductive time is not included in the study.
66. Line 351-352: you talk about a result of case a, matter of this paper, but the result is not in this paper. You can at least write the figures in this discussion section.	ANSWER 66. We added these two sentences (lines 381-383): a) GWP was 31.4 kg CO2e/ m3 s.o.b. when wood chips were burned locally [37] compared to the alternative when they were exported to Sweden. In this case, GWP was 22.9 kg CO2e/ m3 s.o.b. b) Furthermore, the costs of wood chips for heating is more expensive in Norway (97 NOK/m3 s.o.b.) than in Sweden (63 NOK/m3 s.o.b.).
67. Line 372: check grammar.	ANSWER 67. We added the word “viable”
68. Lines 398-400: you should try to support your statements with sentences	ANSWER 68. We deleted this sentence “The Italian system is limited by poorly developed road and rail infrastructure, which limits the technological and technical choices”.
69. Lines 404-405: please be more explicative why chipping is one of the operations with highest emissions, as confirmed by the sensitivity analysis; 20% savings in fuel consumption would imply 19,8% savings in CO2 emissions in this operation, meaning that it may be improved. Or can you explain better you idea?	ANSWER 69. We can reduce fuel consumption (and therefore emissions) by optimizing chipping, which is obtained by feeding the right material, reducing downtime and timely replacing worn knives, among others” We added this sentence: “Fuel consumption and therefore emissions can be reduced by optimizing chipping, which is obtained by feeding the right material, reducing downtime and timely replacing worn knives, among others see…” We quoted the following two references among the ones listed below: Spinelli et al., 2014 and Facello et al., 2013. *Please see:* *Spinelli R., Glushkov S., Markov I. Managing*

	*chipper **knife wear** to increase chip quality and reduce chipping cost (2014) Biomass and Bioenergy, 62, pp. 117-122.* *Facello A., Cavallo E., Magagnotti N., Paletto G., Spinelli R. The effect of **knife wear** on chip quality and processing cost of chestnut and locust fuel wood (2013) Biomass and Bioenergy, 59, pp. 468-476.* *Spinelli R., Magagnotti N. The effect of **raw material, cut length**, and chip discharge on the performance of an industrial chipper (2012) Forest Products Journal, 62 (7-8), pp. 584-589.* *And also:* *Spinelli R., Cavallo E., Facello A., Magagnotti N., Nati C., Paletto G. Performance and energy efficiency of alternative **comminution principles**: Chipping versus grinding (2012) Scandinavian Journal of Forest Research, 27 (4), pp. 393-400.* *Spinelli R., Magagnotti N., Paletto G., Preti C. Determining the impact of some **wood characteristics** on the performance of a mobile chipper (2011) Silva Fennica, 45 (1), pp. 85-95.* “As shown in the sensitivity analysis” was deleted
70. Line 411: same as before regarding the calculation of the input/output ratio. The calculation figures should be within the paper.	ANSWER 70. We added the formula in the text.Please see the answer 43 to reviewer III above
71. Line 428: "chain" is repeated	ANSWER 71. We deleted “chain”
72. Conclusions Lines 456-458: you state that fuel consumption is a critical parameter in GHG emissions from truck transportation and chipping, but in the paper there are only the figures (written within the text) for chipping in Italy.	ANSWER 72. We provided the tables showing the results from the sensitivity analyses for both cases. An explanation is provided in the discussion.
73. Lines 459-461: "the integration of logging residue harvesting with the conventional logging of round wood improved the efficiency of the supply chains". I might have read the paper too quickly, but I don't remember to have seen this analysed in this paper. A table in the discussion, or figures, should be needed. If you refer to the data about SWS in Italy, I think it is not enough.	ANSWER 73.We deleted this sentence
74. Lines 467-468: this is an interesting thought.	ANSWER 74. We agree with the reviewer on

However, I think that forest management, regardless of its objective (bioenergy production, leisure, wood production, etc.) must always be sustainable socioeconomically and environmentally	the fact that forest management should always be sustainable.

*Highlights (for review)

Highlights

- We compare two mountain forest wood fuel supply chains in Norway and in Italy
- Transportation by truck generate the highest emissions in both case study
- The energy use of the Norwegian supply chain was approximately twice as high as the Italian one.
- Changes in fuel consumption affect significantly emissions and energy use from transportation and chipping operations
- Cable yarding and transportation by truck were the most expensive phases respectively in the Italian and Norwegian supply chain.

Mountain forest wood fuel supply chains: comparative studies between Norway and Italy

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Abstract

Case studies of mountain forest wood fuel supply chains from Norway and Italy are presented and compared. Results from previous studies in which greenhouse gas emissions and costs were evaluated using life cycle assessment and cost analysis respectively, are compared. The supply chain is more mechanized in Norway than Italy. Steeper terrain and low road density partly explain the persistence of motor-manual felling in the Italian case. Mechanized forest harvesting can increase productivity and reduce costs, but generates more greenhouse gas (GHG) emissions than motor-manual harvesting. In both cases, the main sources of GHG emissions are truck transportation and chipping. The total emissions are 22.9 kg CO_2/m^3s.o.b. (Norway) and 13.2 kg CO_2/m^3s.o.b. (Italy). The Norwegian case has higher costs than the Italian one, 64 €/m^3s.o.b. and 41 €/m^3s.o.b. respectively, for the overall supply chain. The study shows that mountain forests constitute an interesting source for fuel biomass in both areas, but are a rather costly source, particularly in Norway. The study also exemplifies the care needed in transferring LCA results between regions and countries, particularly where forest biomass is involved.

Key-words: bioenergy, case studies, woody biomass.

[1]**Abbreviations**

1. Introduction

Climate change, due to higher concentrations of greenhouse gases (GHG) in the atmosphere, is becoming an increasingly significant issue. According to the Intergovernmental Panel on Climate Change (IPPC) [1], human activities are the main factor behind rising GHG emissions. The 2013 IPPC report stated emphatically that: "human influences on the climate system are clear" [2, 3]. Underlying this conclusion is the utilization of fossil fuels, which results in an increasing GHG concentration in the atmosphere.

To reduce or at least stabilize the GHG concentration before 2020, emissions of GHGs and particularly CO_2 into the atmosphere need to be reduced. The use of renewable energy can contribute to this, for example by replacing fossil fuels with biomass. However, in the long run equal to forest rotation length, the CO_2 is captured during the tree growth making bioenergy favorable when produced sustainably, i.e. harvest does not exceed growth and soil

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[1]GHG: greenhouse gas

GWP: global warming potential

LCA: life cycle assessment

s.o.b.: solid over bark

condition is maintained. Although further knowledge of the role of soils is need, a sustainably managed forest operation system has great potential for climate change mitigation.

At the global level, the Kyoto protocol has been the key agreement for reducing GHG emissions to date [4]. The protocol ended in 2012 and a voluntary prolongation till 2020 is currently being followed by most, but not all, countries that ratified the original Kyoto protocol. International meetings continue, with the goal of having a new protocol in place by 2020 [5].

In Europe, the European Union (EU) has adopted an energy policy in accordance with international agreements based on a low carbon profile. The goal is to achieve three targets: a 20% reduction of GHG emissions to 1990 levels; an increase in the use of renewable energy to 20% of the total EU energy consumption; and a reduction in total energy consumption [6]. Within the EU, new actions for the period up to 2030 are being discussed. A mixture of all renewable i.e. naturally replenished, energy sources is crucial for achieving these targets. Biomass is one possible choice for the supply of energy which would also reduce GHG emissions, diversify energy supply and reduce pressure on limited resources [7]. Furthermore, it has the potential to be used as a fuel product in addition to producing power, unlike hydro power or wind energy. Woody biomass, agricultural products, slaughter waste, forest products and marine products such as algae are all example of accessible biomass. However, when harvesting biomass, one needs to maintain a balance between what the environment can tolerate, and what is socio-economically viable, i.e. it must be managed in a sustainable way.

Within this variety of renewable resources, woody biomass from forestry is an interesting energy source, already playing an important role in many parts of the world [8]. According to Smeets and Faij [9], biomass from conventional forestry will supply both the forest products industry and energy producers in the future. Woody biomass from mountain forests may be an additional resource for the future, simultaneously promoting socio-economic development.

New opportunities of income and employment in both the forestry and bioenergy sectors may be generated for the local communities in mountain areas.

In Europe, one billion hectares of land, i.e. 36% of the total land surface, are forested, and the rate of forest biomass growth has increased in the last century [10]. Reforestation, i.e., reestablishment of forest cover, is occurring especially on sites once used for grazing and agriculture [11]. Over one quarter of all European forests are mountain forests [12]. Due to their altitude, mountain forests normally have a cooler climate than lower lying areas. Consequently they have a different species composition, slower forest dynamics, regeneration and growth, and a lower intensity of forest operations than lowland forests [13, 14]. A rise in the global average temperature is predicted by the end of this century [15], most likely causing a shift in the tree line to higher altitudes and increase the availability of wood resources.

Around the world, the traditional concept of sustained-yield forestry had to be adapted to the specific conditions of mountain forests, in particular in Norway, to comply with environmental concerns.

The International Energy Agency [7] has predicted a 55% increase in energy demand by 2030, compared to 2000 levels. Currently only 60% of the total forest increment is harvested in Europe and this percentage is even lower in mountain areas [16]. Woody biomass could therefore be an important contributor to satisfying the increased energy demand, but at the same time there will be more and more pressure to find additional sources of wood fuels. Within this context, woody biomass from mountain forests could play a strategic role. Furthermore, in marginal areas, harvesting wood energy can promote rural development [17] and represents a new source of income for forestry companies.

In this study, we focus on two countries, Norway and Italy, with substantially different energy state. Norway is self-sufficient in energy, with domestic energy consumption being dominated by electricity, mainly derived from hydropower (99%). On the other hand, crude oil and natural gas account for almost 50% of the value of all Norwegian exports [18] so Norway is involved in fossil fuel businesses alongside the use of hydropower. Consequently, bioenergy holds a small share (6%) of domestic energy consumption of which domestic users use about 50% for heat production with small wood-burning stoves. In Norway, in 2010, about 53 % of the domestic consumption of wood biofuels for heat production is used in households, 24 % in the pulp and paper production, 11% as wood chips and bark in central district heating, 3% as briquettes and pellets and the remaining 9% in other industries including sawmilling. The market for wood pellets in residential areas is very small, close to zero [19]. At present the Norwegian wood chip market is in decline, partly because of shut downs in the pulp and paper industry and partly because subsidies for chipping of forest residues have disappeared. Productive forests occupy 40% of the Norwegian land area, and the annual increment is more than twice the annual harvest [20]. In 2002, about 30% of the forested area is located in the mountains [21], especially in Hedmark and Oppland counties. In Norway, 49% of forested land has an inclination greater than 20% and most of the potential for increased harvesting is in difficult terrain with low site quality, as is typical of mountain forests [22]. Norwegian mountain forests are managed according to specific rules, which forbid clear cutting and require the maintenance of the mature forest character to protect vital ecological functions. Selective cutting and small-scale clear cutting or group cutting, clear cutting of areas from 0.2 to 0.5 ha, are the conventional harvesting systems for mountain conditions, according to sustainable forest management criteria as specified in Levende Skog [23].

By contrast, Italy is not self-sufficient in energy, and in 2011, the energy dependence from abroad was of 81.3 % [24]. In 2005, more than 30% of the Italian territory is covered with forests, of which 60% are mountain forests [25], generally located in steep terrain.

Traditionally, mountain forests have very long cycles, hence we can assume that the forest situation hasn't changed in the last decade in both case studies.

In Italy, the number of bioenergy plants is increased from 352 to 419 between 2008 and 2009. During the same period, the total power invested grew from 1555 to 2019 MW [26]. As in Norway, traditional wood fuels (i.e. firewood) are mainly used for residential heating. Mountain forests are often integrated into the Natura 2000 European network, subject to specific rules for the preservation of biodiversity. Selective cutting is the only harvesting system allowed in Italian forests. Italian silviculture is largely based on continuous cover forestry (CCF) and applies selection cutting as the main prescription No clear cuts larger than 0.5 ha are allowed on high forests, with the exception of salvage cuts [27].

The goal of this study is to present and compare two forest fuel supply chains in two different regions at the extreme ends of the European continent. The primary objectives are to identify and explain differences, similarities and dominant trends concerning GHG emissions and costs, and energy use as generated by forest management, forest operations, transportation and combustion at the power plant level. Sensitive elements of each supply chain are highlighted. Furthermore, to strengthen our findings we compare our results with previous literature studies. A secondary objective is to provide empirical evidence of the main uncertainties, which may occur when applying our findings to mountain forests having similar, but not identical, conditions to the ones described in our case studies.

2. Material and methods

The object of this study is to compare two real-life examples of forest fuel supply chains in two mountainous countries, Norway -Hedmark/Oppland counties (case a)- and Italy -Fiemme Valley (case b). In the text, the terms "Norwegian case" and "Italian case" indicate generically these two regions.

The system described is quite typical for the Italian Alps, and in general of modern day Alpine logging [28], while the Norwegian system represents common praxis among theoretical elements. At the same time, these case studies offer contrasting economic and cultural environments, as expected for northern and southern Europe, respectively. The fact that conditions are different is an inherent element of any comparison. We believe that the choice of different technical solutions for logging operations, the application of different silvicultural prescription, and the presence of different terrain conditions is an inherent element of any comparison. However, we refer to the tables presented in the appendix 1 for specific study conditions.

In this study, the mountain forest stands in Hedmark and Oppland counties (south-east Norway - case a), grew at an altitude of between 700 m and 1000 m a.s.l. in relatively flat terrain and were harvested for 70% of their total standing volume [14]. As matter of fact, Hedmark and Oppland are characterized by high plateaus located at high altitude, but characterized by minimum slope. Differently it is the situation on the western coast, where the forests are located in steep terrains surrounded by fjords. In contrast, mountain forest stands in Fiemme Valley- case b [29] grew at an altitude of between 1500 and 1800 m a.s.l. in steep terrain having a slope > 40% according to Hippoliti classification [30] had a harvest rate of 35 % to 70% of their total standing volume. In both cases vegetation conditions were similar, characterized by coniferous forests, with Norway spruce [Picea abies (L.) Karst.] as the dominant species.

The studied areas in Hedmark and Oppland counties (case a-Norway) and Fiemme Valley-Trentino-Alto Adige region, Trento province (case b-Italy) are shown in figure 1. The main method for carrying out our case studies was the life cycle assessment (LCA). LCA is a scientific methodology for assessing the environmental impact of products, in this specific case woody biomass for energy, across their life cycle [31]. In this study, the LCA includes the life cycle of forest biomass as an energy product, from raw material extraction at forest stands (cradle) to materials processing (gate), including all transport stages. Use and disposal at the end of the product's life are excluded. LCA assesses the environmental impacts of a system with reference to the ecological system, human health and resource depletion. Our LCA followed the traditional four steps: goal and scope, inventory, impact assessment and data gathering in accordance to ISO standards [32]. In both cases, the functional unit used for evaluating system performance was one solid cubic meter over bark (1 m^3 s.o.b.) of woody biomass, harvested and delivered to a combustion plant. This unit is commonly used in forestry, and bark was included because it contributes to energy production [33]. The conversion factor used for transforming m^3 loose into m^3 s.o.b. was 0.4, while it was 2.12 for transforming m^3 s.o.b. into MWh [34].

The environmental impact category under assessment was climate change, measured through GHG emissions. The characterization model for GHG emissions was their global warming potential (GWP), showing the relative measure of how much infrared radiation (heat) of a greenhouse gas is trapped in the atmosphere in a time horizon of 100 years. This was expressed as $kgCO_{2e\ (equivalent)}/m^3$ s.o.b., for CO_2, CH_4 and N_2O emissions. LCA does not report economic or social impacts. Nevertheless, recently, attempts have been made to include social and economic, as well as environmental, aspects in the LCA methodology for studying product life cycles [35, 36]. In fact, LCA can help to understand whether changes in part of a product life cycle can lead towards greater sustainability. Indeed, in this study, we perform a simplified economic analysis alongside the conventional LCA, based on direct cost accounting and expressed as €/m^3 s.o.b.

The energy use of each process was measured in kWh/m^3 s.o.b.

In the LCA, estimated inputs were: the amount of raw materials and fuel consumption. Estimated outputs were: GHG emissions, costs and energy use. The system boundary, illustrated in figure 2, was the entire supply chain, i.e. a network of different unit processes involved from the forest stand to the combustion plant, including forest management, forest harvesting, biomass transportation and processing. In both cases, the extracted woody biomass was round wood and logging residues (tops and branches). Neither below-ground biomass nor stumps were included in these studies. The harvest of logging residues generally left at the forest stands was integrated with the conventional logging operation (harvesting and forwarding in case a, and felling, extracting and processing operations in case b).

In case study a, it was assumed to allocate 70% of emissions into wood fuel production and 30% into timber production, based on a physical causality approach as mass of outputs. Bundling was only allocated to the wood fuel production. For the transportation from the terminal to the combustion plants, only wood fuels were transported which made it unnecessary to allocate either the input or the output. Regarding case study b, the GHG emissions generated from felling and extraction were charged in relation to the total volume of roundwood and logging residues. Later GHG emissions produced by chipping and chip transportation were allocated only to the logging residues component used for energy purpose, while the timber production chain was excluded by the study. At the DHP, emissions were loaded on wood chips from both logging residues and saw mill residues.

Results from our previous work [14, 29, 37] were used for the comparison of mountain forest wood fuel supply chains in Norway and Italy. Here, we have developed a point-by-point comparison through a new dedicated analysis of the original raw data. This allowed us to pinpoint strengths and weaknesses of the studied chains applied in similar environments but under very different terrain, economic and social conditions. It also allowed us to identify some general trends, as well as account for uncertainty.

In case a, artificial regeneration by soil scarification and planting was assumed to be the normal practice, because it can improve the quality of mountain forests, which today is really poor and thus in the long term generates more wood for energy. Harvesters and forwarders were used for ground-based logging, typical machineries in Norwegian logging operations. Logging residues were separated from round win our ood, assumed to be bundled, forwarded to the landing and then transported to the terminal 64 km away [14]. Here, bundles were chipped and loaded into railroad cars for transportation to biomass plants in neighboring Sweden, 285 km away (134 km by diesel train, and 151 km by electric train). Diesel locomotives were used for the trip to the Swedish border, from where electric locomotives continued to the combined heat and power (CHP) plant [37]. In case b, mountain forests were left to natural regeneration, which is the customary practice in Italy. The whole tree method (WTM) was the assumed logging system in the Italian case. Trees were felled by chainsaw and extracted by cable yarder. At the landing, an excavator-mounted processor delimbed, bucked and stacked logs and logging residues separately. The latter were chipped at the landing and transported by trucks to a local district heating plant (DHP) 30 km away, while the logs were transported to local sawmill and used as construction material [29].

An energy balance (input-output ratio) was estimated as the product between fuel consumption and energy content of fuel, divided by the energy output, i.e. the amount of energy released during the combustion of wood chips at the heating plant. The following equation [38, 39] was used for calculating the energy balance (input- output ratio) of the assortments used for energy production:

$$IE = Fc \times Ec/OE$$

IE is the energy input ratio and it is calculated in percentage. Fc is the fuel consumption of forest machineries in l/m^3 s.o.b., while Ec is the energy content of fuel in kWh divided by OE i.e. the energy output, i.e. the amount of energy released burning wood chips at the combustion plant. The energy output of chips is calculated as the yearly ratio between heat production and wood chip consumption at the plant

In both case studies, woody biomass for bioenergy use was assumed to be carbon neutral, implying that the CO_2 released during the combustion process of the wood fuels is sequestered during the growth of the forest. This concept was the base for assessing the GHG benefits of our mountain forest wood fuel supply chains, where our wood fuel system was assumed to displace fossil fuel at the combustion plants, which otherwise would have been fired with oil, coal or natural gas in case a and fuel oil or natural gas in case b. However, the operations were not completely CO_2 neutral, due to the use of fossil fuels along the supply chains. The CO_2 emissions of machine operations were added to the emissions of CH_4 and N_2O, originated by both supply and combustion. The manufacture of machineries was excluded by the LCA.

Sensitivity analysis was carried out to evaluate how changing the input parameter values can influence the results, and to point out the most critical unit processes along the wood fuel supply chain. Fuel consumption was the increased and decreased input parameter for identifying the effects on energy use and GWP respectively. In case a, GHG emissions and costs were increased and decreased one at time for each unit process. Only in case b, labour cost was the changed input parameter for verifying the impacts on the overall costs.

In case a (from the forest stand to the terminal), results for each process related to GHG emissions and costs were individually decreased and increased by 10% to determine whether changes were smaller or larger than 1.5% compared to the final results [14]. Later, from the terminal to the user, the fuel consumption of each unit process was changed by ± 10% and 20% to check the influence on energy use [37]. In case b, fuel consumption and labour costs were changed by ± 10% and 20% to analyze the effect on GHG and cost levels [29].

3. Results

This section presents the environmental (GWP and energy use) and financial (operational costs) results for each unit process involved in the studied mountain forest wood fuel supply chains (table 1).

In the Norwegian case study, a, the operations with the highest GWP were transportation to the terminal and bundling. In the Italian case study, b, the highest GWP was generated by chipping at the yarder landing and truck transportation of wood chips to the user plant. In both studies, truck transportation generated the highest emissions along the supply chain. The GWP of logging was estimated by summing the emissions of mechanized harvesting and forwarding in case a, and of motor-manual felling, cable yarding and mechanized processing in case b. The resulting GWPs were 7.3 kg CO_{2e}/m^3 s.o.b. and 4.4 kg CO_{2e}/m^3 s.o.b. in case a and b respectively. The logging system adopted in the Norwegian case used 13 kWh/m^3 s.o.b. more than the logging system adopted in the Italian case. In contrast, chipping at the landing (case b) used more energy than chipping at the terminal (case a). The total energy use of the Norwegian supply chain was nearly twice as high as the Italian one. Regardless, the energy balance was very favorable for both systems, and below 5%, i.e. 5 units of fossil fuel energy input were used to produce 100 units of wood fuel energy output. As shown in previous calculation Valente et al. [37], GWP for diesel train was 0.99 kg CO_{2e}/m^3 s.o.b., while GWP for electric train was 0.00001 kg CO_{2e}/m^3 s.o.b. Railway transportation had a low GWP per m^3 s.o.b., when based on hydroelectric power.

Transportation by train made the supply chain more efficient and less air polluting.

Regarding costs, cable yarding was the most expensive process, followed by chipping and truck transportation in case b. Truck transportation to the terminal and bundling were the most expensive processes in the first part of the Norwegian supply chain [14]. However, costs of transportation by truck and train from the terminal to the user were lacking, making it more difficult to discuss the results for the whole Norwegian mountain forest wood fuel supply chain.

Results from the sensitivity analysis are shown in table 2 and 3 for case a and table 4 for case b. Sensitivity analysis showed that emissions from truck transportation and chipping (for case a and b respectively) were most sensitive to changes in the input parameters for fuel consumption, because these operations are the most intensive users of fuel. In the Italian case, for example, a reduction in fuel consumption of 20% for the chipping operation caused a decrease of 1.05 kg CO_{2e}/m^3 s.o.b., while an increase of 20% caused an additional 1.07 kg CO_{2e}/m^3 s.o.b. Changes in fuel consumption significantly influenced the energy use in the second part of the Norwegian supply chain. In case a, bundling was a critical process step, both in terms of GWP and costs, even though it gave lower transport costs later in the supply chain. In case b, cable yarding was very sensitive to changes in operational costs. A change in labor costs of 20% caused a 2.61 €/m^3 s.o.b. increase or decrease in the cost of the overall supply chain. In both case studies, transportation by truck and chipping operations were sensitive to changes in cost factors.

4. Discussion

A low intensity of forest management characterized both Norwegian and Italian mountain forests, being left primarily to natural regeneration. The Norwegian case showed a low cost of forest management in mountain areas due to the simplified management. In case a, the improvement in quality of forest stands through soil scarification and planting was rare. In the last 20 years, there has been a significant decrease in registered planting in Norway. The commercial production of seedling trees seeds adapted to mountain conditions is not feasible at the moment. High labor costs explain why the cost for artificial regeneration assumed in case a is so high. This is confirmed by Lindner [40]. Nevertheless, investments in silviculture would most likely increase future production and value creation, as well as improve environmental protection. In the Italian case, where wood production is one of the main sources of income for forest owners, it is important to apply a forest management strategy that facilitates the socio-economic growth of these areas [41]. It is to highlight that the actual potential of biomass availability is still underutilized in both countries [42, 43].

Nowadays the case study a shows that logging operations were fully mechanized in mountain areas of Hedmark and Oppland.

Harvesters and forwarders are very common in mountain forests, where terrain conditions allow. On the contrary, case b showed the permanence of motor-manual felling and extraction in Italian mountain forests. The main reasons were the technical and economic limitations of using harvesters and forwarders in the steep terrain characteristic of the studied area. However, in recent years, an increased use of mechanical processors has been recorded, which is a sign of the growing modernization of Italian forestry [44]. In the 1970s and early 80s motor-manual logging was also common in Norwegian forests [22] and it was gradually replaced in the 1990s by mechanized harvesting, which was more productive, less time demanding and less costly than the motor-manual system. This allowed a partial offset of the high labor cost and reduced the difficulties in worker recruitment in Norway. Nevertheless, the introduction of mechanized harvesting is associated with an increased use of fossil fuel and consequently an increase in GHG emissions, which explains why logging operations in the Norwegian study had higher emissions than the Italian case. With mechanization in Norway over the last 20 years, the harvesting of difficult and steep terrain has declined dramatically in mountain areas, as confirmed by our case study in Hedmark and Oppland counties. Commercial activities concerning mountain forests only occurred in highlands that were accessible to harvesters and forwarders, while forests growing in steep terrain were not managed at all. This highlights a substantial difference with the Trento province (case b), where steep slopes prevent ground-based logging, thus limiting the introduction of the classic harvester and forwarder team. In that case, loggers have responded with cable yarding, which allows working in difficult terrain and generally results in lower logging damage than ground-based logging [45]. Indeed, cable extraction is commonly used in Southern European mountain forests, as emphasized by Zimbalatti and Proto [46]. In case b, yarding had the lowest GWP impact, but at the same time the largest cost of any process within the mountain forest wood fuel supply chain. Results of the operational costs in the Italian context confirmed low emissions for extraction (1.5 kg CO_{2e}/m^3 s.o.b.) but a high cost of installation for cable yarders, as well as low productivity compared to a classic harvester-forwarder team [47]. Traditional motor-manual short wood systems (SWM) incur even higher costs than the innovative whole-tree extraction method (WTM) presented here for case b [29]. The harvesting cost was 7 €/m^3 s.o.b. higher in the SWM than in the WTM, because of the less efficient motor-manual tree processing, requiring more time and labor [44].

In Norway, the use of cable yarders peaked in the 1980s and then dropped off considerably, due to reduced timber prices, difficulties in finding skilled operators, high operational costs, little technical development and poor public acceptance [22]. However, some efforts are being made to bringing back this technique to the Norwegian west coast [48].

Although there is a constant development of steep terrain harvesting technology, such as self-leveling and tethered machines, that can provide an alternative to cable yarding [49], at the moment these techniques are too costly and may cause heavy environmental impacts.

In Norway, very little forestry residue is used for bioenergy at present. In this study, logging residues were assumed to be bundled and transported by regular timber trucks to the terminal, where they were chipped. Instead in the Italian case, logging residues were chipped at the landing and then transported to the DHP by chip trucks.

Norwegian and Italian plants are not equipped with their own chippers and they also have relatively small log yards, due to the need to keep surface area small, because there is relatively little flat land in mountain areas. That explains why chipping is preferably (although not exclusively) performed at a terminal, rather than at the plant. End use facility chipping system is suitable only for large plants since the investment cost is high. Roadside landing chipping system is suitable also for small plants.

Bundling is an effective system and is economically viable for transportation distances greater than 60 km [50], as shown in case a, because bundles are denser than loose chips and allow larger payloads to be built [51]. However, according to Lindholm et al. [52], bundling forest residues is currently less energy efficient than not bundling since it relies on immature technologies and, as case a showed, is expensive because it introduces an additional process step in the supply system as supported by Spinelli et al. [53]. This cost should be offset by more efficient transportation, storage and comminution. Tests on the use of bundling were actually performed in the Italian Alps [54] including Trentino, corroborating statements about its high cost. At any rate, the short transportation distance made bundling unnecessary. However, according to John Deere [55] bundlers have a significant market in the mountain areas of Spain and South America, with similar conditions to Scandinavia.

In case a, GWP of energy supply were lower when energy wood was exported to neighboring Sweden, rather than being burnt locally (GWP was 31.4 kg CO_{2e}/ m^3 s.o.b. when wood chips were burned locally [37] compared to the alternative where they were exported to Sweden. In this case, GWP was 22.9 kg CO_{2e}/ m^3 s.o.b.). Here, the longer transportation distance was compensated for by the higher efficiency of railway transportation. Furthermore, the costs of the wood chips for heating is more expensive in Norway (97 NOK/m^3 s.o.b.) than in Sweden (63 NOK/m^3 s.o.b.). On the other hand, case b represented the benefits of local use, whereby short transportation distance was a key factor in the reduction of costs, which are anyhow dependent on geographical location [56]. At the moment, Italy is a net importer of wood. Technological innovation, including better boiler efficiency, can make local supplies more competitive, as it may allow mechanized wood processing and integrated biomass and round wood harvesting [57]. In our opinions, in the long run, more intensive production of wood fuels might make alpine areas increasingly self-sufficient in energy.

In Norway, district heating is scarcely developed, representing a very small percentage of the total net energy consumption. This may change in the future as investment support may be established for district heating facilities based on bioenergy. However, the low price of electricity (the main source of heat), the scarcity of infrastructure adapted to district heating, the high investment cost of plants and limited technical development are the main obstacles to the further development of bioenergy in Norway. The high price of wood fuel and high labor costs characterize Norway, compared to other European countries [19]. Hence, the limited internal market for bioenergy makes Norway a net exporter of solid biofuels [58] as confirmed by case a.

From a GHG perspective, rail transportation (case a) was preferable to truck transportation, especially over long distances. In this respect, our findings support other studies [59]. Rail transportation in Finland, for example, is economically viable with road transportation over distances greater than 160 km. Furthermore, rail transportation has positive effects on the reduction of CO_2 emissions [60]. However, at the moment most wood products are generally transported by truck [61]. The cost of transportation by truck is higher in Norway than in neighbor countries, due to stricter road regulations (e.g. lower maximum vehicle sizes compared to Sweden), higher fees and poorer roads [22].

In Nordic countries, terminals ensure the constant availability of wood chips, by providing storage capacity to buffer any temporary mismatches between demand and supply, and by consolidating more product streams from different sources. The capacity of CHP plants to accept low-quality fuel, thus reaching a higher efficiency of the fuel input, and the superior efficiency of rail transportation make it more effective in this case to export Norwegian biomass to Sweden, than to use it locally [37]. Currently biomass for CHP plants and DHPs has limited competitiveness in most countries due to the high costs for producing biofuels, but increasing energy prices in general mean it will become more and more profitable in the near future. Furthermore subsidies will have to be introduced to reach the EU targets for renewable energy, making biomass more attractive. In Sweden, there have been strong incentives to invest in bioenergy plants for many years due to the heavy taxation of fossil fuels and to programs like the green electricity certificates. A different situation is found in Norway, even though, according to Trømborg et al. [62] forest residues have great potential for bioenergy production in Norway, when the demand for bioenergy increases [63]. In the short term, it is predicted that a decrease in the availability of sawmill residues and a parallel increase in their price will make it necessary to use forest residues to produce wood fuels in order to match the increased demand for bioenergy. Therefore, a combination of harvesting forest residues, chipping at the terminal, railway transportation for long distances and large scale CHP plants may have considerable development potential in Norway, as shown in other studies from Scandinavia [52, 64, 65].

Italy has embraced a decentralized user model, aimed at favoring local consumption and minimizing transportation distances. This implies a lower need for terminals, whose use is not very common in Italy, in line with new logistical trends on stock reduction. In Alpine areas, chipping at the landing is still the most efficient system [66]. However, the productivity of industrial chipping at a terminal is usually higher than achieved at the forest landing [67]. In both case studies, chipping was one of the operations with the highest emissions. Fuel consumption and therefore emissions can be reduced by optimizing chipping, which is obtained by feeding the right material, reducing downtime and timely replacing worn knives, among others see Spinelli et al. [68] and Facello et al. [69]. The location of wood biomass comminution, i.e. the process by which solid materials are reduced in size by chipper, influences the whole supply chain [70] and is strictly tied to local conditions.

Regarding the energy balance (input-output ratio), fuel supply absorbed a small portion (below 5%) of the energy released during combustion, indicating that these chains are energetically attractive, so supporting the results from other studies [52, 65, 70]. However, all these authors reported under lowland conditions, where energy inputs were slightly lower than in our cases. Energy input was higher in the Norwegian case than in the Italian one, due to the longer transportation distance, the introduction of the bundling operation and the comminution at the terminal, which increased loading work.

The Italian case study had lower emissions, energy use and costs than the Norwegian case. The main explanation was the less mechanized and simpler supply chain; more process steps (silviculture, bundling, and terminal) were involved in the Norwegian case. However, differences could also depend on variation in the availability and quality of data, data collection methods and assumptions. Technical choices are connected to the location of mountain forests; steep terrain in Italy versus flatter terrain in Norway. Concerning the assessment of sustainability, our main findings were comparable with results from ToSIA, a tool for evaluating the sustainability of forest wood supply chain [40]. For example, low mechanization involves less efficient logging operations, but at the same time higher labor demand and costs.

Finally, we should remember that it is important to guarantee respect of the environment in all its shapes, e.g. preserving biodiversity, through sustainable forest management [71]. The harvesting of wood biomass from mountain areas will have additional goals beyond energy wood production alone, and the introduction of selective cutting for bioenergy production may create a more natural-looking forest stand, thus achieving an aesthetic goal as well.

5. Conclusions

In this paper, we present two complete case studies of mountain forest wood fuel supply chains in Norway and Italy. Different ways of managing the supply chain makes it difficult to draw wide generalizations. As such, the study exemplifies the care needed in transferring LCA results between regions and countries, in particular where forest biomass is involved. Nevertheless, it is possible to extend our results to conditions similar to those described above. Based on our results, we can conclude that it is realistic to source woody biomass, including logging residues, from mountain areas. Energy input-output ratios were similar to previous studies made in lowland conditions suggesting that the energy input into mountain forest woody biomass operations is far below the output of the harvested fuel. The GHG emissions avoided by the substitution of fossil fuel with bioenergy were large, especially when wood chips substituted coal and fuel oil.

Intensive harvesting and excessive mechanization can affect the stability of mountain ecosystems, and increase emissions from forestry operations. The sensitivity analysis suggested that fuel consumption was a critical parameter in the GHG emissions of both truck transportation and chipping. Regarding costs, extraction by cable yarder in Italy and transportation by truck in Norway were the most expensive operations. Low intensity of forest management characterized the sites of both our case studies. Active forest management could improve the quality of forest stands and the availability of wood biomass for bioenergy, but these benefits have to be weighed against the financial cost of the operation. Further studies might address other environmental impact categories, such as acidification and eutrophication, the sustainability of energy systems and ethical aspects, especially concerning the type of forestry we want for the future in mountain areas. In particular, one may question whether it is environmentally and socio-economically sustainable to dedicate specific mountain forest stands to bioenergy production, either alone or in combination with extracting sawlogs and pulpwood. In conclusion, the two case studies show that the forest resources in European mountain regions may be an additional resource of biomass for the future, with possibilities to fulfill some of the shift to a green carbon economy.

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Table

Table 1: GWP. costs and energy use of each unit process considered in Norwegian (case a) and Italian (case b) supply chains

Process	GWP		Costs [a]		Energy use	
	$kgCO_{2e}/m^3$ s.o.b.		€/m^3 s.o.b.		kWh/m^3 s.o.b.	
	Case a	Case b	Case a	Case b	Case a	Case b
Silviculture (soil scarification)	0.04	-	4.50	-	0.16	-
Regeneration	0.23	-	10.04	-	0.85	-
Logging operations	Harvesting	Felling	Harvesting	Felling	Harvesting	Felling
	3.04	0.10	10.12	2.38	11.33	0.30
	Forwarding	Extraction	Forwarding	Extraction	Forwarding	Extraction
	4.24	1.25	9.00	13.06	15.81	4.22
	-	Processing	-	Processing	-	Processing
		3.02		7.32		10.16
	Bundling		Bundling		Bundling	
	4.45	-	11	-	16.59	-
Transport the terminal	5.55	-	13.20	-	20.68	-
Chipping	3.60	5.29	6.00	10.07	12.12	17.80
Loading	0.75	-	n.a.	-	2.52	-
Transport to the plant	railway	roadway	n.a.	roadway	railway	roadway
	0.99	3.54		8.51	21.81	11.92
Total (rounded off)	22.90	13.20	64.00	41.00	102.00	44.00

[a] 1 euro=8 NOK; n.a. = not available; – = not included

Table 2. Sensitivity analyses of the final results related to GHG emissions and costs: reduction (-10%) and increment (+10%) of each unit process in case a (Norway).

	GHG emissions		Costs	
	-10%	10%	-10%	10%
Silviculture	-0.03	0.02	-0.73	0.72
Regeneration	-0.13	0.13	-1.46	1.41
Harvesting	-1.46	1.41	-1.47	1.42
Forwarding	-1.88	1.79	-1.33	1.29
Bundling	-1.94	1.84	-1.57	1.51
Terminal	-2.23	2.09	-1.74	1.72

Table 3. Sensitivity analysis of the Norwegian wood fuel productive chain (case a): decrease and increase of 10% and 20% of the parameter fuel consumption and effect on the energy use (kWh/m^3 s.o.b.).

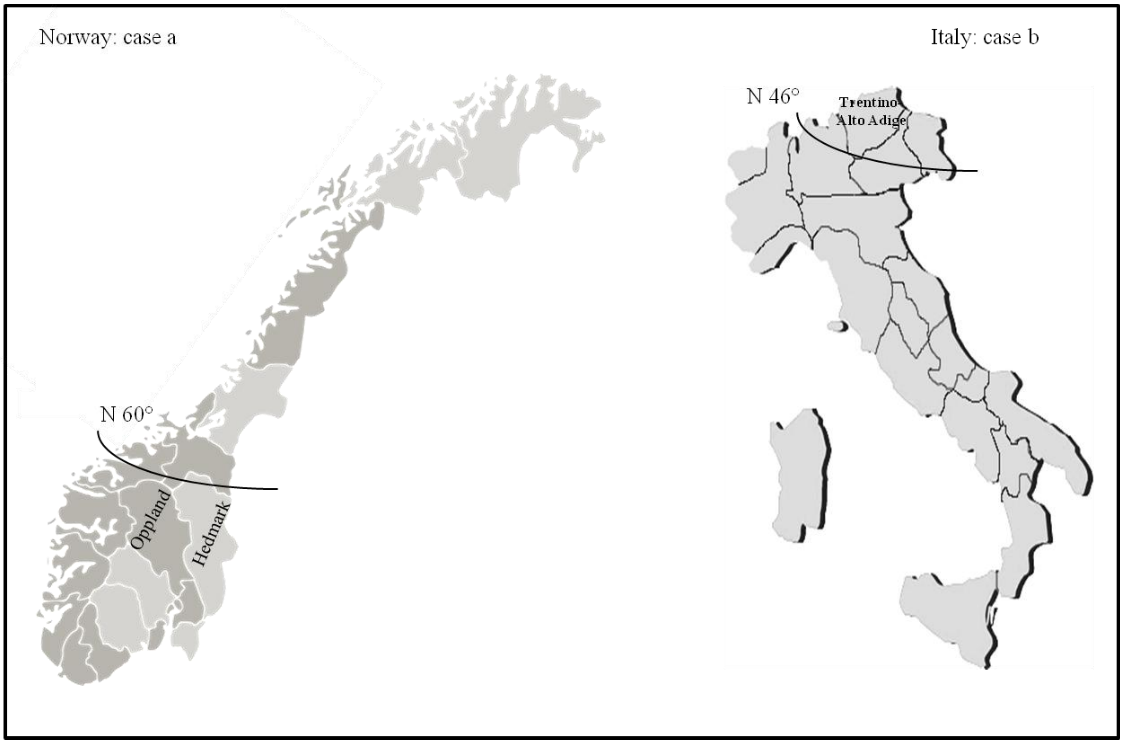
	Energy use (kWh/m^3 s.o.b.)			
	-20 %	-10 %	10 %	20 %
Chipping	-9.70	-10.91	13.33	14.54
Loading	-2.02	-2.27	2.78	3.03
Transport Truck	-17.45	-19.63	24.00	26.18
Transport Diesel Train	-2.67	-3.00	3.67	4.00
Transport Electric Train	-1.57	-1.76	2.16	2.35

Table 4. Sensitivity analyses: variation of GWP and production costs achieved in the base case (base). increasing and decreasing fuel consumption and labor cost of 10% and 20% of each operation one at a time in case b (Italy)

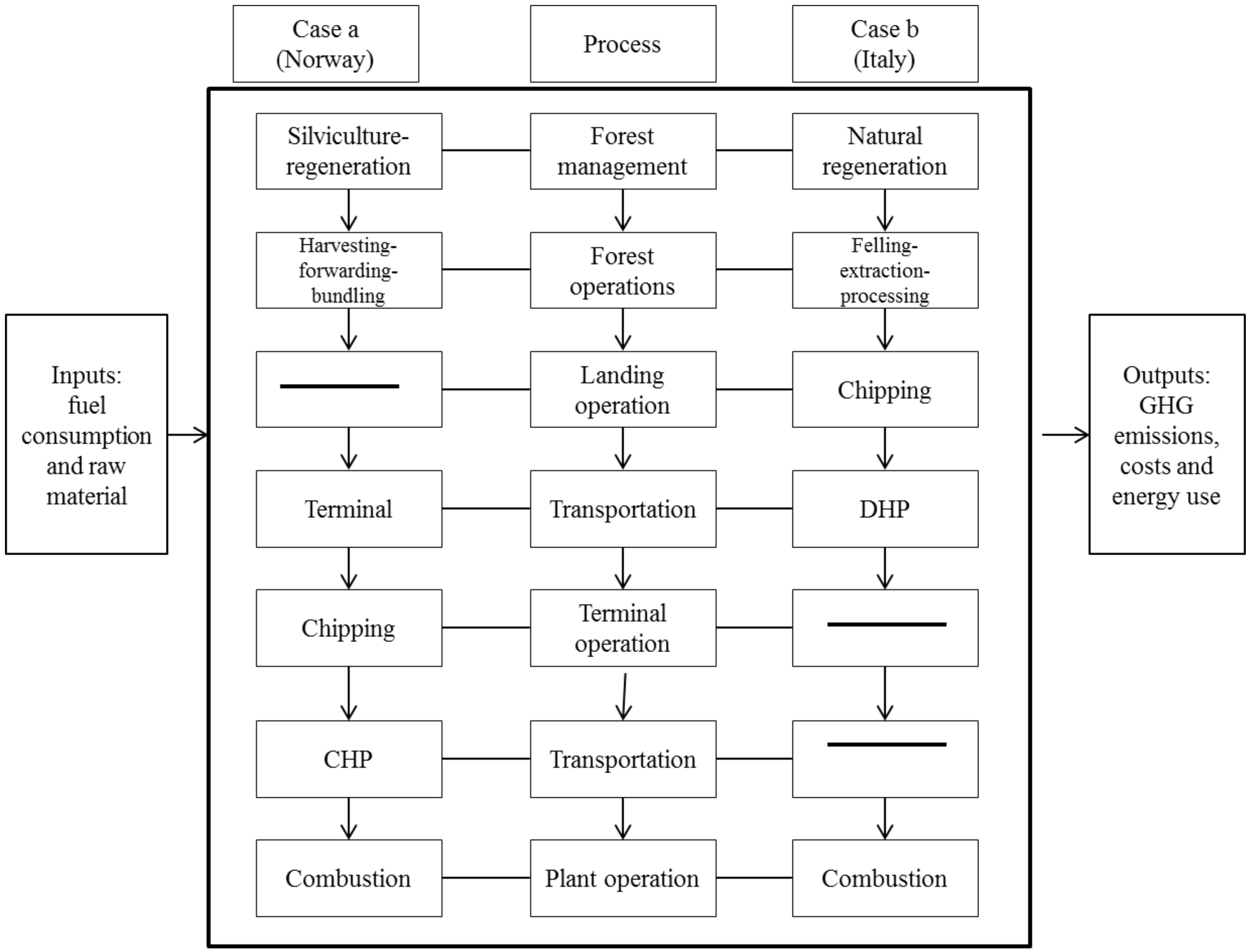
	GWP ($kgCO_{2e}/m^3$ s.o.b.)					Costs (€/m^3 s.o.b.)				
	base	-20 %	-10 %	10 %	20 %	base	-20 %	-10 %	10 %	20 %
Stump site op.	0.1	0.08	0.09	0.1	0.12	2.38	1.87	2.12	2.63	2.89
Extraction	1.25	1	1.13	1.38	1.5	13.06	10.45	11.7	14.32	15.67
Landing op.	3.02	2.41	2.71	3.32	3.62	7.32	5.88	6.6	8.04	8.75
Chipping	5.29	4.24	4.77	5.84	6.36	10.07	8.25	9.25	11.31	12.38
Transport	3.54	2.79	3.18	3.89	3.89	8.51	7.04	7.86	9.69	10.48

Figure 1: Geographical location of case studies: Hedmark and Oppland counties -Norway and Fiemme Valley-Trentino-Alto Adige region, Italy.

Figure 2: System boundaries of the Norwegian and Italian mountain forest wood fuel supply chains: case a and b respectively on the left and right side and assessed processes in the centre.



Norway: case a
Italy: case b
N 60°
Oppland
Hedmark
N 46°
Trentino
Alto Adige


Case a (Norway)
Process
Case b (Italy)
Silviculture-regeneration
Forest management
Natural regeneration
Harvesting-forwarding-bundling
Forest operations
Felling-extraction-processing
Landing operation
Chipping
Terminal
Transportation
DHP
Chipping
Terminal operation
CHP
Transportation
Combustion
Plant operation
Combustion
Inputs: fuel consumption and raw material
Outputs: GHG emissions, costs and energy use

APPENDIX 1

Table 1. Main data and assumptions for case study a (Norway)

Variable	*Assumptions*
Total woody biomass amount	13474 m^3 (stemwood) and 4777 m3 (logging residues)
Density for woody biomass	900 kg/m^3 s.o.b.
Transport	Roundwood and bundles: 64 km (from landing to terminal)
	Wood chips: 285 km (134 km by diesel train. and 151 km by electric train): terminal-plant
Loading capacity of truck	50 tons
Amount of wood chips at the terminal	163000 m^3 loose/year of which 123000 m^3 loose/year are delivered to the Swedish plant
Moisture content of wood chips	30% for round wood and 50% for logging residues (based on personal communication)
Emission factors used for machineries	CO_2: 3.17 kg/t; N_20: 0.12555 kg/t; CH_4: 0.09688 kg/t
Energy content (diesel)	36.22 MJ/l

Table 2. Main data and assumptions for case study b (Italy)

Total woody biomass amount	6966 m3 s.o.b.
Biomass expansion factor	Additional 0.26 m3 equivalent of biomass per m3 s.o.b. of round wood (the amount of logging residues was measure in dry tons and then transformed in m3 s.o.b.using the biomass expansion factor.
Energy and moisture content for roundwood and logging residues	9.08 MJ/kg at 45% moisture content
Density of both round wood and logging residues	715 kg/m^3 s.o.b.
Transport distance to the forest stand to DHP	30 km
Loading capacity of trucks	6.3 ton dry matter chips
Energy content and density of wood chips	Density: 287 kg/loose m^3 or 393 kg/m^3 s.o.b. (dry). Energy content: 0.72 MWh/loose m^3
Wood chips consumed in 2008 at DHP	13709 m^3 s.o.b.
Heat production at DHP	28 GWh
Emissions factor	
CO_2	74100 Kg/TJ
CH_4	4.15 Kg/TJ
N_2O	28.6 Kg/TJ
Diesel	
Density	0.8439 kg/l
Net calorific value	43 TJ/Gg