QUANTIFICATION OF ENVIRONMENTAL PERFORMANCE INDICATORS EPIS FOR FOREST ROADS

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Keywords: Environmentally sound technologies ESTs, forest road infrastructure, Life Cycle Inventory Analysis, energy efficiency, greenhouse gas emissions

Abstract: *The application of resource efficient environmentally sound technologies ESTs has become crucial for both development and environment. Operationalization of ESTs requires a methodology to quantify a set of operational performance indicators OPIs for a specific infrastructure or production system. A well-established hypotheses states that forest roads networks have a share of about 60 percent in the overall environmental burden of the timber procurement process. However, there is a lack of understanding of how slope conditions, cross-section geometry, geology, and pavement structure affects environmental performance indicators.*
The paper aims (1) to give some background information on the concepts of environmentally sound technology and environmental performance evaluation, (2) to provide a methodological approach based on input-output modeling to quantify the inflow of environmental resources, and the outflow of emissions respectively, and (3) to present results of indicator studies (energy input, CO_2 output) for a standard forest roads. The energy input for one unit of length of a forest road is about 350 MJ per meter, what is equivalent to a calorimetric heating value of 10 liters of diesel fuel. Increasing the slope to 70 percent triples energy input. The present approach allows to evaluate the spatial variability of operational performance indicators for forest roads on steep slope conditions. It is an important step towards environmental performance evaluation EPE, as proposed in the ISO standard 14'031.

1. Introduction

In the complex relationship between development and the environment, technology provides a link between human action and the natural resource base. Faced with limited global natural resources, the people of the world must seek to achieve more sustainable forms of development. The application of resource efficient environmentally sound technologies ESTs has become crucial for both development and environment (UNEP, 2000). Land use is the starting point of anthropogenic triggered mass and energy flows. The formulation of environmentally sound land use policies presupposes (1) knowledge about resource use and emissions for specific production systems [system knowledge], and (2) well-supported ideas on how a near-optimal land use strategy would look like [target knowledge]. At present, only few studies, which analyze efficiency of resource use and output of emissions and wastes of forest production systems, have become available (Karjalainen and Asikainen, 1996; Zimmer and Wegener, 1996; Knechtle, 1997; Winkler, 1997; Berg, 2000). Those studies that are mainly based on cases indicate that about 60% of the overall environmental burdens of forest production are caused by road network infrastructure and long-distance transport (Karjalainen and Asikainen, 1996; Winkler, 1997; Heinimann, 1999). There are two major shortcomings of the previous studies. First, they simply summed up indicators for selected cases. Second, they did not use a formal approach to describe structure and behavior of the underlying physical process networks.

The transportation system of the forest sector is a starting point for an improved understanding of production soundness due to its high share in the environmental burdens of the whole system. The paper aims to quantify energy input and greenhouse gas output for the process of forest road construction. It will first give some background information on the concepts of environmentally sound technology EST and environmental performance evaluation EPE. Then, it will provide a methodological approach based on input-output modeling to quantify the inflow of environmental resources, and the outflow of emissions respectively. Finally it will present results of indicator studies (energy input, CO_2 output) for a standard unit of a forest road.

2. Background

Environmentally Sound Technologies ESTs are an essential component to improve environmentally soundness of anthropogenic activities. They are not just "individual technologies, but total systems which include know-how, procedures, goods and services, and equipment as well as organizational and managerial procedures" (UNEP, 2000). Environmental Performance Evaluation EPE (ISO, 1999) is one approach to quantify the “soundness” of those technologies, which can assist an organization in identifying its environmental aspects; determining which aspects it will treat as significant; setting criteria for its environmental performance; and assessing its environmental performance against these criteria. The following sections describe the key aspects of the EPE concept, define relevant terms, and present an approach to quantify EPE.

2.1 Environmental Performance Concept

The concept of environmental performance covers two different views (ISO, 1999). The first looks into a specific organization, and the second looks outside to the environment (figure 1). Organization-specific performance indicators are called environmental performance indicators EPIs while the state of the environment is characterized with environmental condition indicators ECIs. The present paper investigates environmental performance of forest roads, which only relates to the operations part of an organization that is characterized by operational performance indicators OPIs (figure 1). All indicators (EPIs, OPIs, ECIs and MPIs) aim to make EPE comparable and comprehensible.

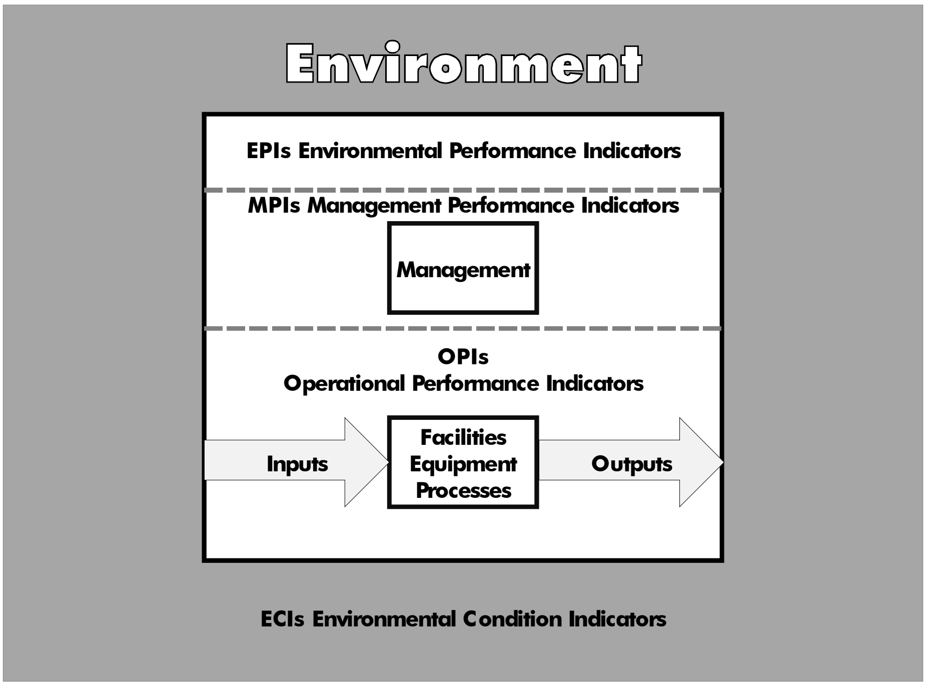

Figure 1: ISO 14031 environmental performance evaluation framework, according to (ISO, 1999). There are two types of indicators: (1) environmental condition indicators ECIs , and (2) environmental performance indicators EPIs consisting of operational performance indicators OPIs and management performance indicators MPIs.

Since the environmental performance evaluation concept has not yet been widely introduced into the forest operations community, some of the key definitions related to it will be given in the following paragraphs.

Environmental Sound Technologies ESTs	Environmentally Sound Technologies (ESTs) encompass technologies that have the potential for significantly improved *environmental performance* relative to other technologies. Broadly speaking, these technologies protect the environment, are less polluting, use resources in a sustainable manner, recycle more of their wastes and products, and handle all residual wastes in a more environmentally acceptable way than the technologies for which they are substitutes (UNEP, 2000).
Environmental Impact	any change to the environment, whether adverse or beneficial, wholly or partially resulting from an organization's activities, products or services (ISO, 1999)
Environmental Performance	results of an organization's management of its environmental aspects, e.g. elements of an organization's activities, products or services that can interact with the environment (ISO, 1999)
Environmental Performance Criterion	environmental objective, target, or other intended level of environmental performance set by the management of the organization and used for the purpose of environmental performance evaluation (ISO, 1999)
Environmental Performance Indicator EPI	specific expression that provides information about an organization's environmental performance (ISO, 1999)

Operational Performance Indicator OPI	environmental performance indicator that provides information about the environmental performance of an organization's operations (ISO, 1999)
Eco-Efficiency	Eco-efficiency is reached by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing environmental impacts and resource intensity throughout the life cycle, to a level at least in line with the earth's estimated carrying capacity (DeSimone and Popoff, 1997).
Environmental Condition Indicator ECI.	Specific expression that provides information about the local, regional, national or global condition of the environment. "Regional" may refer to a state, a province, or a group of states within a country, or it may refer to a group of countries or a continent, depending on the scale of the condition of the environment that the organization chooses to consider (ISO, 1999).
Life-Cycle-Assessment LCA	Compilation and evaluation of the inputs and the potential environmental impacts of a product system through its life cycle (ISO, 1997).
Life-Cycle-Inventory Analysis LCIA	Phase of life cycle assessment involving compilation and quantification of inputs and outputs, for a given product system through its life cycle (ISO, 1997).

2.2 Life Cycle Approach

There are several approaches to quantify environmental performance indicators, such as "cause and effect approach", " risk-based approach", "life cycle approach" (ISO, 1999). The present analysis follows the "life cycle approach" by selecting and considering the inputs and outputs associated with the construction of forest roads, and the significant environmental aspects and impacts at any stage of a road's life cycle. Inputs consist of materials and energy, which enter into the process network (source flow). Output covers materials and energy, which leave the process network (sink flow). The life cycle approach therefore analyzes the flows of energy, materials, emissions, and wastes through the whole process network from sources to sinks. Table 1 provides examples of OPIs that may be appropriate to measure environmental performance of an organization's operations.

Table 1: Selection of Possible Operational Performance Indicators OPIs, according to (ISO, 1999).

OPI Type	*OPI Class*	*Possible OPIs (selected from ISO 14031)*
Input	MATERIALS	quantity of raw materials reused in the production process; quantity of water per unit of product; quantity of hazardous materials used in the production process.
	Energy	quantity of energy used per unit of product or service; quantity of each type of energy used; quantity of energy generated with by-products or process streams.
	SERVICES	amount of hazardous materials used by contracted service providers; amount of cleaning agents used by contracted service providers; amount of recyclable and reusable materials used by contracted service providers; amount or type of wastes generated by contracted service providers.
	Facilities and Equipment	total land area used for production purposes; number of emergency events or non-routine operations (e.g. shut-downs) per year.
Output	WASTES	quantity of waste per year or per unit of product; quantity of waste stored on site; quantity of waste converted to reusable material per year.
	Emissions	quantity of specific emissions per unit of product; quantity of waste energy released to air; quantity of air emissions having ozone-depletion potential; quantity of air emissions having global climate-change potential.

3. Methodology

3.1 Subject Matter Model

Life Cycle Inventory Analysis aims to compile and to quantify all relevant inputs and outputs of process network (ISO, 1997), which are needed to construct a forest road (figure 2). Production economics provides a formal approach to investigate process networks or even economic sectors, which relies on two fundamental concepts: (1) commodities, and (2) activities (Koopmans, 1951). An activity, also called a process, consists of a specific technology, which transforms specific input-flows into output-flows according to well-defined procedures. Mapping of process networks as flows on a graph has become an important approach to analyze environmental impacts (Leontief, 1970; Ayres and Noble, 1978; Leontief, 1986; Heijungs et al., 1992; Heijungs, 1997; Frischknecht, 1998). Activities are represented as nodes while arcs represent flows of goods, resources, emissions, and wastes. The resulting graph is non-cyclic, directed and finite. Additionally, several source nodes and sink nodes may exist, being located outside of the system's boundaries. This type of graph has also become known as GOZINTO-graph, following “the part that goes into”.

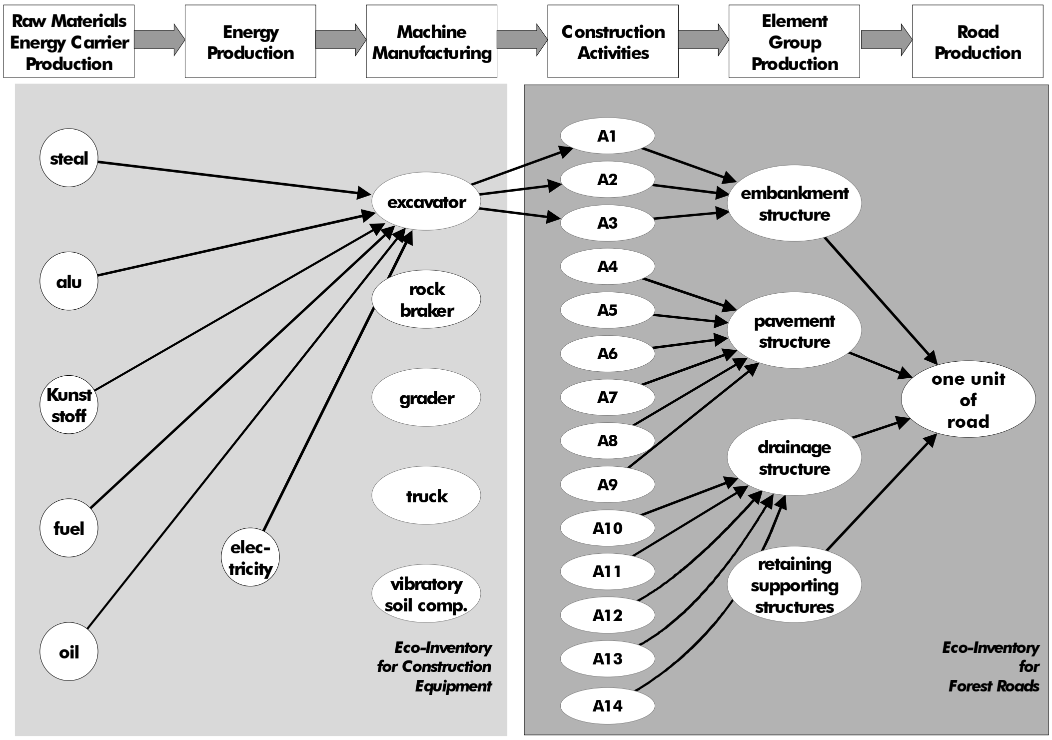

Figure 2: Mapping the flow of energy, materials, emissions, and wastes for forest road construction as a directed graph. Note: to maintain clarity of the figure, only a subset of the relevant flows has been reproduced.

Figure 2 illustrates a directed graph, which represents the activity-flow structure of the road construction process network. It considers several stages of the life cycle: (1) production of raw materials and energy carriers, (2) energy production, (3) machine manufacturing, (4) construction activities, (5) element group production, and (6) road manufacturing. In a cradle to grave approach, three additional phases should be considered, use, maintenance, and decommissioning, which are neglected in the present analysis. Life cycle inventory analysis aims at compiling and quantifying all relevant inputs and outputs of a given system. The overall system (figure 2) was split into two subsystems in order to reduce complexity and to improve flexibility by module building. The first subsystem, life cycle inventory for construction equipment, analyzed environmental burdens of five machine types, excavator, rock breaker, grader, truck, and vibratory soil compacter. The resulting burdens will be used as inflows into the second subsystem, life cycle inventory for forest roads. It consists of 14 construction activities, which are typical for the current practices in the European Alps. They are used as inputs for the next life cycle phase, element group production, which considers (1) embankment structure, (2) pavement structure, and (3) drainage structure. A fourth element group, retaining and supporting structure, was not considered in the present analysis, although it may be important, especially on slopes steeper than 50 percent.

3.2 Formalized Description of the Process Network

Numerical analysis requires the conceptual model of figure 2 being translated into a mathematical model. Flows on a graph may be represented by a system of linear equations. Each row describes the flow of one commodity. There is a convention to map source flows with positive, and sink flows with negative figures. Using matrix notation [1] results in a flow matrix A with n rows, representing n commodities, and with m columns, representing m activities. Such a matrix that is unique for a specific process network is called technology matrix A. Activities (columns) are assumed linearly scalable. The set of scaling factors is represented by a scaling vector X with length m. A unique solution requires (1) a quadratic technology matrix a (m equals n), and (2) a known balance of inflows and outflows for all commodities. The balance boundary conditions are represented by a vector Y with length n.

$$A \cdot X = Y \qquad [1]$$

Model analysis is complete, if we know the vector X. It can be found by solving matrix equation [1] for X [2].

$$X = A^{-1} \cdot Y \qquad [2]$$

Equation [2] completely describes the flow of commodities for a given process network. For life cycle inventory analysis, the model has to be enhanced to analyze the flow of environmental burdens. There is a well-documented approach (Leontief, 1970; Ayres and Noble, 1978; Leontief, 1986; Heijungs et al., 1992; Heijungs, 1997; Frischknecht, 1998) which assumes the flow of commodities to be proportional to the flow of environmental burdens. A single type of environmental burden may be represented by a vector B, which has the same length as the scaling vector X. If p types of environmental burdens have to be considered, activity specific environmental burdens may be mapped on a matrix B that has p rows and m columns.

$$b = B \cdot X \qquad [3]$$

Multiplying the burden matrix B by the scaling vector X results in the burden vector b of the total system [3].

3.3 Data Gathering

The first step of information gathering consists of choosing the right environmental performance indicators. Indicators should (1) concern with a global business value or environmental issue, (2) be relevant to virtually all businesses and (3) have an agreed measurement method and definition (Verfaillie et al., 2000; WBCSD, 2000). Additionally, they should foster continual improvement and make sectors and industries comparable across time. Generally applicable indicators for product/service value are (Verfaillie et al., 2000):

- Quantity of goods or services produced or provided to customers
- Net sales

Those relating to the environmental influence in product/service creation are (Verfaillie et al., 2000):

- Energy consumption
- Materials consumption
- Water consumption
- Greenhouse gas emissions
- Ozone depleting substance emissions

A unit length of one meter was used in the present study to quantify the commodity "forest road". Energy consumption and greenhouse gas emissions served as indicators for environmental impact. Energy through flow measures as MJ (Megajoules) per unit length of road. Additionally, it will be given in high (gross) heating value (HHV) equivalents of diesel fuel. Greenhouse Gas (GHG) Emissions including CO_2, CH_4, N_20, HFCs, PFCs and SF6 will be given in kilograms of CO_2 equivalents.

The specification of the flow parameters for the "construction equipment" subsystem was done as follows:

- Commodity inflow, measured in mass (kg) per machine for each type of raw material, was estimated according to manufacturer's information,
- Inflow of environmental burdens for each type of material was taken from a standard life cycle inventory (Frischknecht et al., 1996),
- Commodity outflow was measured in productive machine hours (PMHs),
- Outflow of environmental burdens was calculated according to [3].

The specification of the flow parameters for the "forest road" subsystem was done as follows:

- Commodity inflow into the construction activity layer, measured in productive machine hours (PMHs) for each type of machine, was estimated from productivity figures,
- Commodity inflow into the element group layer was calculated for one volume unit (embankment, pavement), or for one length unit (drainage),
- Commodity inflow into the road layer resulted from the dimensions of the road cross section, which depends on slope, roadbed width, cut slope angle, fill slope angle, and geological formation,
- Emissions of combustion processes were taken from literature.

4. Results and Discussion

What follows, is the result of model analysis for road parameters, which are typical for mountainous areas of Switzerland. The analysis is based on the following assumptions: (1) a roadbed width of 4.2 m, (2) a cut slope angle of 1:1, (3) a fill slope angle of 4:5, (4) a thickness of the base course of 0.3 m, (5) a thickness of the surface course of 0.08 m, and (6) a transport distance for base course materials of 10 kilometers. The influence of the three most important factors, slope, transport distance for base course materials, and roadbed width will be given in the following figures.

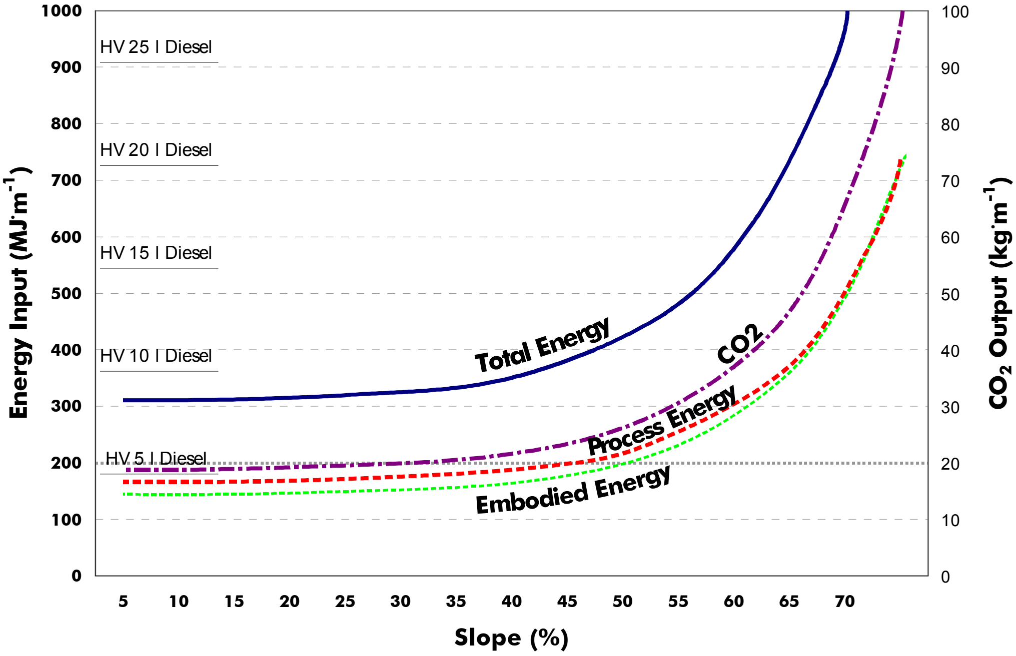

Figure 3: Influence of slope on energy input and CO$_2$ emissions. Assumptions: road bed width 4.2 m; cut slope 1:1, fill slope 4:5; thickness of base course 0.3 m, thickness of surface course 0.08 m; transport distance for base course materials 10 km. HV gross heating value of diesel fuel

Figure 3 illustrates the influence of slope on energy inputs and greenhouse gas outputs. Forest road construction consumes about 350 megajoules of energy per meter, to which process energy contributes about 50 percent. The effect of increasing slope is obvious for slopes steeper than 40 percent. Road construction on a 60 percent slope doubles energy consumption whereas a slope of about 70 percent triples energy use. Assuming a heating value for diesel fuel of about 36 megajoules per liter results in a heating value equivalent of about 10 l of diesel per meter for moderate slopes, 15 l of diesel per meter for medium slopes, and 20 l of diesel per meter for slopes of about 70 percent. Those energy consumption figures are about four times higher than the rough estimates, which can be found in literature. Consumption of process energy was estimated by about 1.3 l of diesel fuel per meter of road (Karjalainen and Asikainen, 1996). Greenhouse gas output is more or less proportional to energy consumption. Assuming that the growth of 10 kg dry wood mass can sequestrate about 18 kg of CO$_2$ results in a required sequestration capacity of about 10 kg wood mass for one meter of road on moderate slopes. This value triples for slopes of about 70 percent.

Figure 4 shows the influence of transport distance of road base course materials on energy inputs and greenhouse gas output. On site preparation of aggregate materials is the environmentally most friendly approach, corresponding to an energy consumption equivalent of about 6 l of diesel fuel per meter. Energy consumption increases by about 20 megajoules per additional kilometer of transport distance. A transport distance of about 50 kilometers increases energy consumption by a factor of about five compared to on site preparation. Greenhouse gas output is proportional to energy consumption.

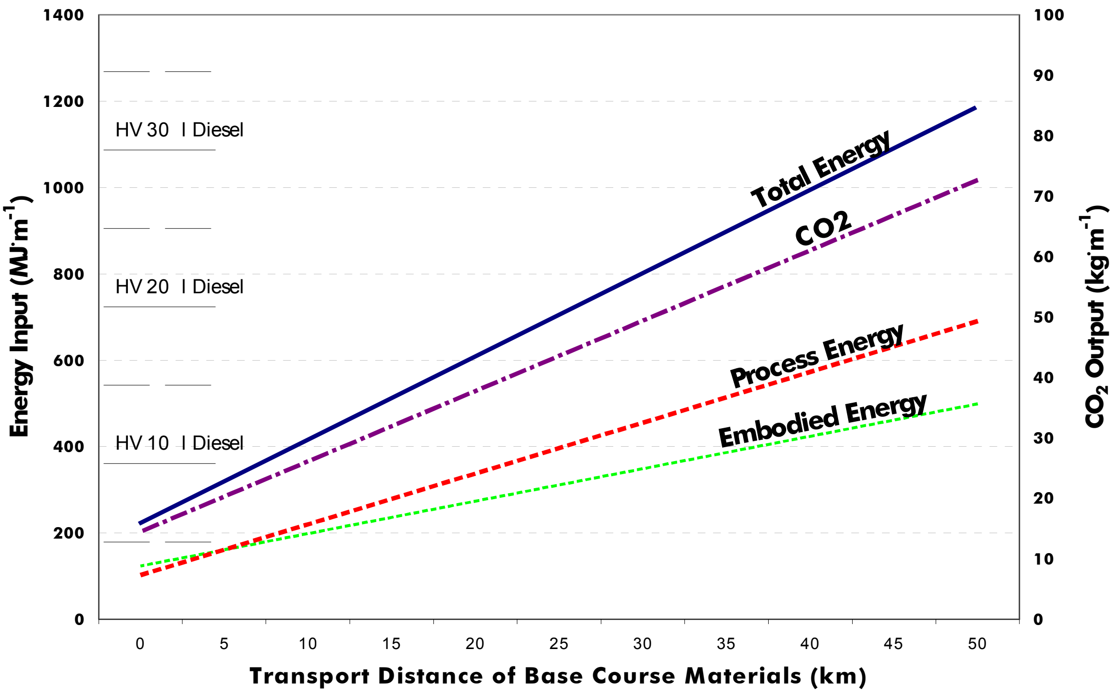

Figure 4: Influence of transport distance for base course material on energy flow. Assumptions: road bed width 4.2 m; cut slope 1:1, fill slope 4:5; thickness of base course 0.3 m, thickness of surface course 0.08 m; slope 50%. HV gross heating value of diesel fuel.

Figure 5 illustrates the influence of road bed width on energy consumption. The reference roadbed width is 4.2 m. Reducing the width by about 1.5 m results in a decrease of energy consumption by about 50 percent, whereas increasing roadbed width by about 2 m to 6.2 m doubles it.

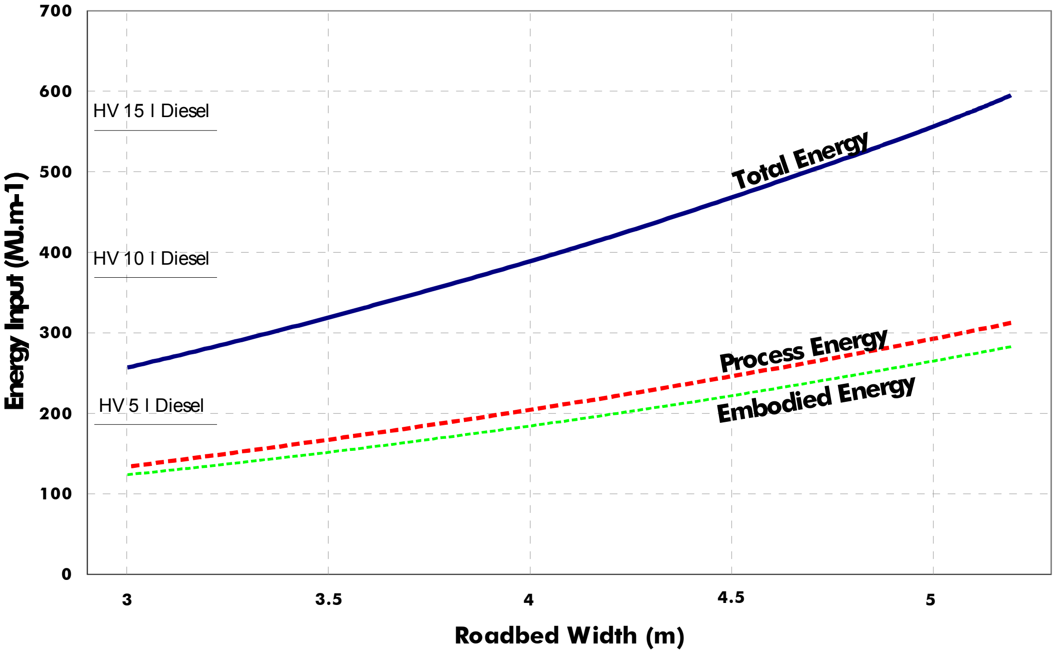

Figure 5: Influence of roadbed width on energy input. Assumptions: cut slope 1:1, fill slope 4:5; thickness of base course 0.3 m, thickness of surface course 0.08 m; transport distance for base course materials 10 km; slope 50%. HV gross heating value of diesel fuel.

5. Conclusions

The study aimed at developing an input-output model to quantify energy use and greenhouse gas emissions for forest road construction. It followed a life cycle approach, which considered embodied energy and embodied emissions of earlier production phases, such as raw material manufacturing, equipment manufacturing, and fuel production. The study resulted in the following main findings. (1) On moderate slopes up to 40 percent, construction of one meter of forest road consumes about 350 megajoules of energy while emitting about 20 kg of greenhouse gases. (2) Energy consumption is equivalent to the heating value of about 10 l of diesel fuel per meter of road length, and about 10 kg of wood mass that has to be grown to sequestrate the amount emitted greenhouse gas. (3) Transport distance of base course materials is the most sensitive factor of influence. Compared to on-site preparation of aggregates, a 50-kilometer transport increases energy consumption by a factor of about five. (4) Slope is the second important factor that shows a nonlinear influence on energy consumption and greenhouse gas emissions. Increasing slope to about 50 percent doubles energy consumption and greenhouse gas omissions, while a slope of 70 percent almost triples them. (5) Roadbed width is the third important factor of influence. Energy consumption doubles by increasing it from 4.2 m to 6.2 m.

The present study is the first that evaluates environmental performance of forest road construction based on an input-output model of the underlying process network. This approach makes it possible to study the influence of 6 road construction parameters: (1) roadbed width, (2) cut slope, (3) fill slope, (4) thickness of base course, (5) thickness of surface course, and (6) transport distance of base course materials. Modular conception (figure 2) of the model is another advantage, which makes model use very flexible. Environmental burdens of raw materials and energy carriers were taken from a life cycling inventory (Frischknecht et al., 1996), which is typical for Switzerland. However, it would be very easy to adapt the model to different regional conditions by considering country-specific life cycle inventories. Further research will focus on model refinement, especially by considering different types of construction practices. Another challenge is to investigate the whole forestry production process by integrating the present road model with life cycle inventory models of the whole forest operations network, which will be an important step towards an integrated system of environmental performance evaluation EPE, as proposed in the ISO standard 14'031.

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