Energy Efficiency in Dairy Cattle Farming and related Feed Production in Iran

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In the name of God

.

This work is presented to:

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Who taught me a letter, made me his devotee. (Imam Ali)

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Hail to knowledge, the knowledge houses and the men of knowledge who are the torch of guidance and the guide of nations towards sublimity and blessedness and excellence and grace. (Imam Khomeini)

Abstract

Dairy farming is increasing and becoming more intensive, attendant on higher energy inputs, also in Iran. The aim of this study was to estimate and assess the energy efficiency of dairy farming and the related feed production in north-western Iran. Data were gained from a company producing feeds in north-western Iran, and from 24 dairy farms, also in north-western Iran for a period of three years. A method of investigation was devised based on the cumulative energy demand (CED) method introduced by VDI guideline 4600 and ISO standard 14044, which is used in life cycle assessment (LCA).

The energy intensity (EI) in the feed production (in MJ kg^{-1} DM) was 2.92 for alfalfa, 6.76 for barley grain, 9.19 for maize corn, 12.36 for rapeseed, 2.45 for spring maize silage, 4.45 for summer maize silage and 4.35 for wheat grain. The EI for the energy corrected milk (ECM) was 5.84±0.69 MJ kg^{-1} with a ECM yield of 6,585±1,221 kg cow^{-1} yr^{-1}. Feedstuff was the main source of energy input in milk production, with approximately 79% of the total energy input. The EI was decreasing with an increasing milk yield (-0.36 MJ kg^{-1} ECM per +1,000 kg ECM cow^{-1} yr^{-1}), within the range of the milk yield found in the investigated farms (3,860-8,320 kg ECM cow^{-1} yr^{-1}). The energy input was allocated to milk (83%), manure (15%) and meat (2%). The EI for boneless meat produced by bulls up to 400 kg body mass was 75.4±9.1 MJ kg^{-1} and produced by bulls up to 700 kg was 103.8±11.4 MJ kg^{-1}. The allocated EI for meat of the replacing slaughtered cows was 16.3 MJ kg^{-1} of meat.

By calculating the EI for milk production on the basis of the higher heating value (HHV) of feeds, it yielded in a mean EI of 23.7±3.37 MJ kg^{-1} ECM and an EI of 314±25 MJ kg^{-1} bull meat (400 kg body mass).

Energy output input ratio (OIR) ranged between 2.03 MJ MJ^{-1} for maize corn and 7.75 MJ MJ^{-1} for spring maize silage production. While, in milk production OIR was 0.55 MJ MJ^{-1} and in meat production 0.12 MJ MJ^{-1}.

Keywords:

Cumulative Energy Demand, Dairy, Energy Intensity, Feedstuff, Iran, LCA

Kurzfassung

Umfang und Intensität der Milchviehhaltung nehmen immer weiter zu, dies gilt auch für den Iran. Das Ziel dieser Studie waren die Ermittlung und Bewertung der Energieeffizienz der Milchviehhaltung und Futterproduktion im nordwestlichen Iran. Daten wurden auf einem Futterbaubetrieb und auf 24 Milchviehbetrieben im nordwestlichen Iran erfasst. Es wurde eine Untersuchungsmethode erarbeitet, die auf der VDI-Richtlinie 4600 Kumulierter Energieaufwand (KEA) und dem ISO-Standard 14044 Umweltmanagement – Ökobilanz basiert.

Die Energieintensität (EI) im Futter (in MJ kg^{-1} DM) lag bei 2,92 für Luzerne, bei 6,76 für Gerste, bei 9,19 für Mais, bei 12,36 für Raps, bei 2,45 für Frühjahrsmaissilage, bei 4,45 für Sommermaissilage und bei 4,35 für Weizen. Die EI der energiekorrigierten Milch (ECM) lag bei 5,84±0,69 MJ kg^{-1}, bei einer Milchleistung von 6.585±1.221 kg ECM Kuh^{-1} Jahr^{-1}. Die Futter waren die Hauptquelle des Energie-Inputs in die Milchproduktion, mit einem Anteil von 79%. Innerhalb der in den untersuchten Betrieben vorgefundenen Milchleistung (3.860-8.320 kg ECM Kuh^{-1} Jahr^{-1}) verringerte sich die EI bei steigender Milchleistung (-0,36 MJ kg^{-1} ECM je +1.000 kg ECM Kuh^{-1} Jahr^{-1}). Die Allokation des Energie-Inputs führte zu einem Anteil von 83% auf dem Milch, 2% auf den Fleisch und 15 % auf den Wirtschaftsdünger. Die EI des mit Bullen bis zu einer Körpermasse von 400 kg produzierten Schlachtfleisches lag bei 75,4±9,1 MJ kg^{-1}, bei Fortführung der Mast bis zu 700 kg lag sie bei 103,8±11,4 MJ kg^{-1}. Die EI bei ersetzten, geschlachteten Milchkühen bei 16,3 MJ kg^{-1} Fleisch lag.

Die Kalkulation der EI auf Basis des Brennwert der Futter, führte zu einer EI in der Milchproduktion von 23,7±3,37 MJ kg^{-1} ECM und in der Erzeugung von Bullenfleisch (400 kg Körpermasse) 314±25 MJ kg^{-1}.

Das Energie Output-Input-Verhältnis (OIR) lag zwischen 2,03 MJ MJ^{-1} für Körnermais und 7,75 MJ MJ^{-1} für Frühjahrsmaissilage. Während OIR in der Milch 0,55 MJ MJ^{-1} und in der Fleisch 0,12 MJ MJ^{-1} betrug.

Keywords:

Energieintensität, Futtermittel, Iran, Kumulierter Energieaufwand, LCA, Milchviehhaltung,

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Abbreviations

CED	Cumulative Energy Demand
DEV	Digestible Energy Value
DM	Dry Matter
EE	Energy Efficiency
EEV	Embodied Energy Value
EI	Energy Intensity
EP	Energy Productivity
ECM	Energy Corrected Milk
EMA	Environmental Management for Agriculture
ESI	Environmental Sustainability Index
FCM	Fat Corrected Milk
FM	Fresh Matter
GEMIS	Globales Emissions-Modell Integrierter Systeme
HHV	Higher Heating Value
HRR	Heifer Replacement Rate
IFIAS	International Federation of Institutes for Advanced Studies
ISO	International Organisation of Standards
KUL	Kriterien Umweltverträglicher Landbewirtschaftung
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LEP	Labour Energy Productivity
LHV	Lower Heating Value
LM	Live mass
MEV	Metabolisable Energy Value
ME	Metabolisable Energy
NEL	Net Energy Lactation
NEV	Net Energy Value
NEY	Net Energy Yield
NRC	National Research Council (of the USA)
OIR	Output/Input Ratio
R&M	Repair and Maintenance
REPRO	Reproduktion der Organischen Substanz
SEJ	Solar Equivalent Joules
TDN	Total Digestible Nutrition
VDI	Verein Deutscher Ingenieure (Association of German Engineers)

1 Introduction

The population of the world is growing. In 2000, the world population was 6.1 billion, and it is estimated that there will be an increase to 8.2 billion people by 2030 (Schneider, 2010). The security of the food that will feed this growing population is a significant challenge. Recently, more than 3.7 billion people were faced with malnourishment (Pimentel, 2009). In 2010, it was determined that of these 3.7 billion, 925 million people, mostly in developing countries, were undernourished, and these numbers have been increasing worldwide since 1995 (FAO, 2010). However, agriculture produces enough food to overcome future demands. Poverty and undernourishment of a large part of the population is caused by fundamental problems in the distribution of food and resources (FAO, 2002).

Agriculture plays a role in the improvement of food security worldwide by contributing to the growth of the economy in most developing countries and thereby reducing poverty (Pingali and McCullough, 2010). Livestock farming is an important sector of agriculture that contributes intensively to these aspects of food security. The demand for livestock products is increasing. The increase in demand for livestock products is growing more rapidly than the population growth rate (Schneider, 2010). Because of population growth, increasing living standards and shifting demographic parameters (e.g., urbanisation and rising incomes), the demand for animal products has increased (Steinfeld et al., 2006). Global production of milk and meat in 2050 is projected to be more than double the production of 1999 (Steinfeld et al., 2006), an increase that is being called the Livestock Revolution (Devendra, 2002).

At the same time, agriculture is seriously challenged by environmental problems such as the reduction of water quality and farmland quantity due to erosion, developing infrastructures, and extensive grazing (Steinfeld et al., 2006). Increasing debate regarding the impact of agriculture on the environment has led to less use of chemical fertilisers and pesticides and more restrictions on greenhouse gas emissions. It is assumed that these restrictions will lead to a decrease in the production yield (Börjesson, 1996). Therefore, to compensate for these restrictions and increase food production, the use of more intensive, mechanised, and precise agricultural systems is unavoidable, which will cause higher energy consumption in food production. However, the depletion of the fossil fuel stocks and increasing oil prices may result in a further decrease in energy consumption.

Energy efficiency improvement is one of the most important aspects in regard to combatting these challenges. Energy efficiency improvements contribute to the reductions of emissions and climate change (Varone and Aebischer, 2001) and are a solution for fuel resource restrictions. The study of energy flow and energy efficiency will allow us to recognise bottlenecks and, subsequently, improve the production processes to achieve systems with more energy efficiency.

Energy efficiency first garnered attentions after the oil crisis and resulting increase in oil prices in the 1970s (Zuberman, 2009). Primarily, economic and political indicators and later, environmental issues (linked with the consumption of fossil fuels), brought the reliability of production systems and the dependency on fossil fuels to the forefront. With this goal in mind, Life Cycle Assessment (LCA) models were introduced to assess the life of a production process. In 1974, after some individual works the International Federation of Institutes for Advanced Studies (IFIAS) in Stockholm tried to standardise energy efficiency investigations so that the results of different studies could be compared (Zuberman, 2009). At the 1992 International Environment and Development Conference in Rio de Janeiro, new guidelines and indicators were introduced to support the assessment of national and international development processes in regard to sustainability (UN, 1992). These attempts led to the introduction of several standards and guidelines, such as VDI 4600 in 1997 (revised 2012) and ISO 14041 in 1998 (revised by ISO 14044, 2006). Additionally, several software models have been introduced to help to analyse the systems. Some examples of these models are the KUL-method (Eckert et al., 1999) and REPRO (Hülsbergen, 2003) in Germany, EMA system (Lewis & Bardon, 1998) in Britain, and ESI-method (Sands & Podmore, 2000) in the USA.

Agriculture is one of the three main economic sectors (in addition to industry and services) (Schäfer, 2003) that consume energy resources and emit greenhouse gases (GHG). Scientists have investigated and assessed the energy efficiency of agricultural systems. Farming practices (which differ in intensity), region, crop type, and management have been evaluated by energy efficiency indicators. These studies showed a reduction of the energy output input ratio (OIR) in more intensified systems because the increase in the yield was less than the increase in the consumption of non-renewable energy resources, such as fuels and fertilisers (Pimentel et al, 1973; Pimentel et al., 1998; Kuesters and Lammel, 1999).

The energy efficiency of livestock production is lower than that of crop production (Pimentel, 2009). In comparison to crop production, few studies have been conducted on the energy efficiency of livestock farming (Wechselberger, 2000). The number of intensive livestock systems is increasing, and the land and livelihood needs of extensive systems are crucial challenges of livestock farming (Schneider, 2010). There is insufficient knowledge about the energy efficiency of production technologies in animal husbandry, in addition to little information on how targets and intensity of production may influence energy efficiency.

There is a rapidly increasing demand for dairy products in Iran, as well as in most developing countries. Pastures in Iran are mainly low in quality and sensitive to overgrazing due to the primarily dry climate (Badripour, 2006). Therefore, most feedstuffs used in cattle farming are produced intensively on farms in competition and rotation with foodstuff production. The use of croplands for the production of feedstuffs or consumption of grains as feedstuff to meet the increasing demand of livestock production is a threat to the sustainability of the food supply in Iranian agriculture.

The aim of this study is to estimate and assess the energy efficiency of dairy cattle farms and feedstuff production farms in common systems that are prevalent in north-western Iran. The most useful indicators in energy efficiency investigation in the production of feedstuffs and also dairy products are the energy intensity (EI) and energy output input ratio (OIR). These indicators are calculated for both milk and meat from dairy cattle farms. The comparison of the energy efficiency of several farms that differ in herd size, cattle breed quality, keeping systems and management makes it possible to determine which systems are more efficient and trace more efficient processes and activities inside these systems.

To preserve a scientific and standard method of investigation and to be able to assess and compare the production processes with other similar studies, the Cumulative Energy Demand (CED) concept described by VDI guideline 4600 (2012) and the Life Cycle Assessment (LCA) concept specialised by ISO standards 14040 and 14044 (2006) were used. Sensitivity analysis described the uncertainties of the results and identified connotative fields for further investigations.

2 Literature review

2.1 Agriculture and livestock farming in Iran

Agriculture is one of the most important sectors of Iran’s economy. Currently, agriculture constitutes 13.9% of the total gross domestic product (GDP) and 30% of non-oil exports from the country (Rabii, 2011). According to FAO, Iran ranks among the top 7 countries in the production of 22 important agricultural products. In comparison to the previous year, the value of agricultural production increased by 20% in the Iranian calendar 1389 (ending March 2011), and agricultural exports rose by 30% (Rabii, 2011).

The total land area of Iran is approximately 165 million hectares, consisting of 54.6% rangeland, 7.5% forests, and 20.6% deserts, and the remaining 6% are other settlements, infrastructures, and water. Approximately, 33 million hectares have good capacity, on average, for agriculture, but just 18.5 million ha (12% of total land area) are cultivated. Of the cultivated land, 8.5 million ha are irrigated, and 10 million ha are rain fed (Badripour, 2006). Therefore, agriculture is correlated with rainfall, and the amount of rain that falls on the region is the most significant challenge of the Iranian agricultural sector. The annual rainfall is 264 mm, which is less than one-third of the world’s average precipitation.

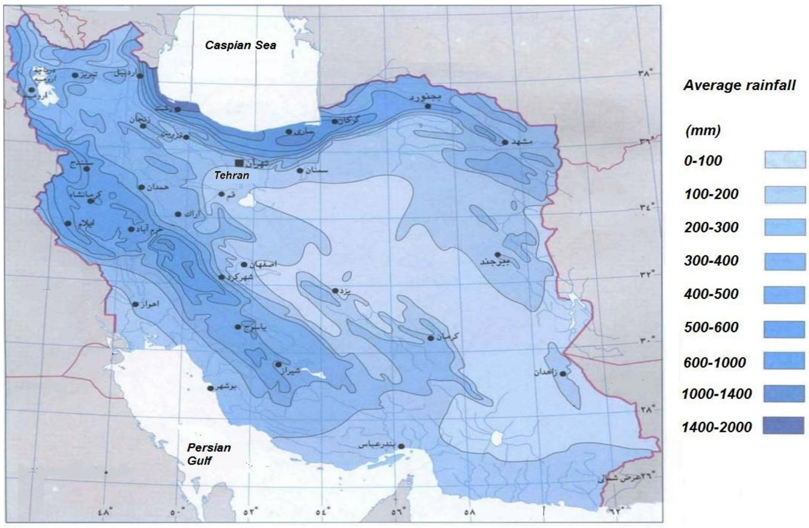

Figure 1 Average annual rainfall map of Iran.

The mean altitude is 1,200 m above sea level. The lowest point is the coast of the Caspian Sea, at 27 m below sea level, while the highest point is Damavand Mountain, at 5,670 m above sea level. The southern half of the county is in the subtropical zone, the northern half is in the temperate zone, and there is a desert zone in the middle of the country. These contrasting zones cause high diversity in the climate across the entire country (Badripour, 2006).

Livestock farming constitutes 6% of the total GDP of Iran. There are nearly 83 million animal units[1] in the country. Only 37 million animal units can be fed by range for 7 months per year, leaving an excess of 46 million animal units (Badripour, 2006). Therefore, some of the arable land is under cultivation for feedstuff for livestock in competition with foodstuff production. However, a significant share of feedstuff is imported yearly, depending on the yearly rainfall rate.

Table 1 Range condition in Iran (Badripour, 2006).

Condition	*Area (million ha)*	*Mean DM yield (kg/ha)*	*Useable DM (million tonnes)*
Fair – Good	14	290	4.0
Poor – Fair	60	92	5.5
Very poor – Poor	16	26	0.5
Total	90		10.0

According to FAOSTAT, in 2006, the livestock numbers comprised 54 million sheep, 26 million goats, and 7.9 million cattle. In 2011, these numbers were 49, 23.5, and 8.6 million, respectively (FAOSTAT, 2012). In 2011, the average whole fresh milk yield per cow was 2.2 tonnes per year with a total of 6.4 million tonnes of milk across the country (FAOSTAT, 2012). The statistical portal of the agricultural ministry of Iran claims that the total milk production was 7.8 million tonnes in 2006 and 10.8 million tonnes in 2011 (MAJ, 2011). The difference between these two statistics may refer to the estimation of produced milk on small dairy farms, where the producer consumes the products or they sell their products directly to private individuals. These farms are not included regularly in the statistical surveys. Additionally, the statistics of the agricultural ministry include milk produced by sheep and goats, as well as from buffaloes and camels.

Based on the diversity in climate and the demographic culture, in addition to the population density, there are different systems of agriculture and animal husbandry all over the country. These systems have been adapted to each region and climate over a long period of time. The difference between livestock systems appears in the breed purity of the livestock, the feedstuff fed to the livestock, keeping systems, herd size, and managerial patterns. Sheep

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[1] Animal unit means a unit of measurement for any animal feeding operation (University of Illinois: agricultural and horticultural extension). An animal unit (AU) in Iran was defined as a sheep of 45 kg mass, which requires 276.5 kg TDN per year (Badripour, 2006). Accordingly, in Iran, a pure breed Holstein cow is 9.5 AU, cross breed cattle is 6.5 AU, local cattle is 4 AU, buffalo is 6.5 AU, goat is 0.75 AU, camel is 5.5 AU, and horse and ass is 4.5 AU (MAJ, 2007).

and goats are kept mostly extensively, while cattle, buffalo, and camel are kept intensively and in barns in the vicinity of villages and cities.

The breed composition of cattle population in Iran in 2006 consisted of 8.6% Holstein with a milk yield of 6,634 kg per year and cow, 45.4% crossing of Holstein and local breeds with a yield of 2,827 kg per year and cow, and 46.0% local breeds with yield of 864 kg per year and cow (Amar, 2006). Breed purity improving programs in the country has been planned to change from local breed to Holstein breed.

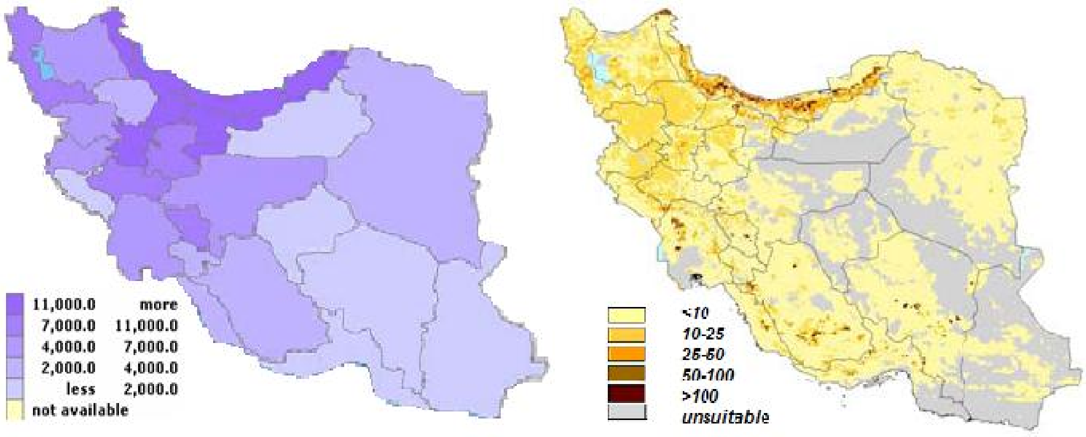

Figure 2 Density of milk production in kg per km^2 (left) and the cattle population in heads per km^2 (right) in Iran (FAO, 2005)

The two main systems in cattle farming are traditional and industrial. As reported by the statistic centre of Iran in 2006, traditional livestock farming was generally practiced in rural locations and comprised approximately 85% of the total cattle population, while industrial farms had a share of only 15% of the total cattle population (Amar, 2006). However, there have been an increasing number of cattle raised on industrial farms in recent years (see figure 3).

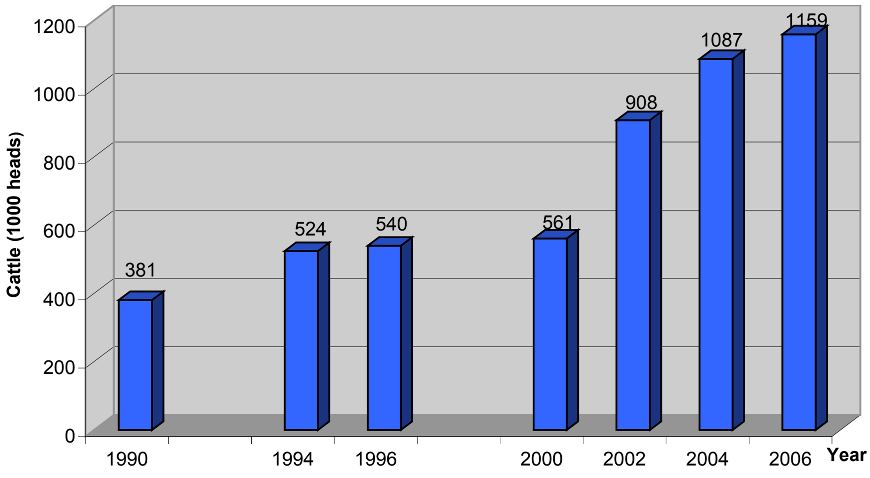

Figure 3 Number of industrial raised cattle in Iran from 1990 to 2006 (Amar, 2006).

The term “industrial dairy farm” refers to farms that adjust their barns, facilities, management, feeding program, and cattle breed to the new methods and scientific techniques introduced by the agricultural ministry and experts (Amar, 2006). This definition is independent of the herd size, but most industrial farms have larger herds than the traditional farms. On some industrial farms, the number of cattle is over 20,000. The feedstuff of these farms is generally not produced on site, but is instead bought from external providers. Only 5% of industrial farms have the availability to include a grazing program to supplement half of the feeding of cattle (Amar, 2010), while in rural farms, this availability is higher. However, there are also no regular grazing programs on rural farms. Grazing is often limited to a short session and is performed on the after-harvest residues. As shown in table 2, most of the cattle population in Iran in 2006 were kept on farms consisting of 10 or fewer head (88% of total cattle holders). Thirty-one percent of the cattle were kept in 11-50 head herds, and only 15% were kept in herds bigger than 50 head.

Table 2 Classification of holders and dairy cow population by herd size (Amar, 2006)

Herd size	*Holders population (%)*	*Cattle population (%)*
1-10	88	54
11-50	11	31
51-100	0.5	5
101-200	0.2	4
201-500	0.06	3
More than 500	0.01	3
Total number	1,321,531	7,609,358

2.2 Historical background of energy analysis

High dependency on fossil fuels is one of the challenges of intensive agricultural systems and has been a source of interest to researchers for many years. After the oil crisis in the 1970s and the subsequent increasing oil prices, some studies have been introduced and developed with the goal of improving the management of fossil fuel consumption in agriculture. Howard Odum, David Pimentel and Robert Constanza were among the pioneers and most prominent researchers involved in evaluating the energy balances in agricultural systems and trying to increase energy efficiency (Zuberman, 2009). Pimentel published his first study in 1973. His method consisted of quantifying the amount of energy input in the form of either working hour, mass of materials, fuels or machinery and comparing them with the energy output from the products. In the same manner, he converted energy inputs into economic prices. He introduced indicators that allowed for the energy inputs to be compared with the outputs and for the energy efficiency of a system to be evaluated. In 1974, the International Federation of Institutes for Advanced Studies (IFIAS) conducted a workshop in Stockholm with the aim of producing of a set of definitions, conventions and standards to be recommended for general use by those working with the analysis of energy (IFIAS, 1975).

Most of the data needed in energy analyses, such as the energy equivalent of embodied energy in inputs, are from the 1970s (Börjesson, 1996). For example, in 1972, Berry and Fulton investigated the embodied energy in car factories, and Pimentel et al. (1973) extended their study by estimating the embodied energy in agricultural machinery, a finding that is still used in energy analyses (Mikkola and Ahokas, 2010). Constanza (1980) discussed different methods used in input-output analysis and outlined the main factors in boundary designing and consideration of direct and indirect energies. In addition to these individual studies, other attempts were made to provide standards and guidelines to establish a standard methodology of energy assessment worldwide that has been used to this day. The VDI guideline 4600 was introduced in 1997 by an association of German engineers (VDI) to develop a cumulative energy demand investigation, which was revised in 2012. The GEMIS database (Globales Emissions-Modell Integrierter Systeme), which was established in 1989 (GEMIS ver. 1, 1989), also used this guideline in 1999 (GEMIS ver. 3.x, 1999) to enable the analysis of energy and emission in production processes. Both the VDI guideline and the GEMIS database were used by Kraatz (2009) to investigate the energy efficiency of dairy farming in Germany.

ECOINVENT is another database that was established in 2000 in Switzerland that is used to provide LCA data (ECOINVENT, 2007). The GEMIS database (GEMIS ver. 4.81, 2012) and ECOINVENT database (ECOINVENT ver. 3.0, 2013) were revised in 2012 and 2013, respectively.

Most of the energy investigation methodologies are focused on the energy and economic indicators. To avoid neglecting other issues, such as the environmental effects of the consumption of energy resources (especially non-renewable energies), the life cycle assessment (LCA) methodology was introduced in the 1970s, primarily in beverage companies (e.g., Coca-Cola) (Zuberman, 2009). The LCA methodology is used to assess the impact of a production system on the environment. This method has become more and more important. The International Organisation of Standards (ISO) developed ISO 14041-3 standards in 1998 and 2000 for LCA concept, which were revised in 2006 by ISO 14040 and ISO 14044 (2006). With the increasing complexity of the indicators and their relation to emissions, several software models were introduced to help to analyse the systems. Some of these models include the KUL-method (Eckert et al., 1999) and REPRO (Hülsbergen, 2003) in Germany, the EMA system (Lewis & Bardon, 1998) in Britain, and the ESI-method (Sands & Podmore, 2000) in the USA.

2.3 Methodologies of energy analysis

According to the IFIAS (1974), the energy analysis is defined as the “determination of the energy sequestered in the process of making a good or service within the framework of an agreed set of conventions or applying the information so obtained”.

The IFIAS method consisted of the following steps:

- Establishing the boundary of the process under analysis.
- Identifying all the factors involved in the process.
- Assigning an energy equivalent to each factor.
- Multiplying the energy equivalent by the quantities required by each factor.
- Identifying and quantifying the end product. Allocating the consumed energy to the main product and by-product.
- Relating the energy content of the product with the energy consumed in its production, which means defining suitable indicators to evaluate the efficiency of the process.

In the IFIAS methodology, the energy equivalent of each factor is defined as its thermodynamic heating content. There are no differences between different qualities or hierarchies of energy sources (Zuberman, 2009). Therefore, the indicators used in the evaluation are in fact based on the first law of thermodynamics[1], referring to the thermal or enthalpic efficiency of a system. With such indicators, the energy quality of inputs and outputs is not taken into account, which is a significant disadvantage of their use (Patterson, 1996). One of the solutions to overcome this problem is to quantify the inputs and outputs by means of their work ability and the exergy concept, which are based on the second law of thermodynamic (Patterson, 1996). Another way to combat this disadvantage is the use of the emergy (energy memory) concept. Emergy attempts to quantify all the useful energy (exergy), both directly and indirectly, through the entire process of obtaining a product. Odum proposed this method in 1996 (cited in Zuberman, 2009). Because the first and main energy input in each system is from the sun, the unit of measure of emergy is expressed primarily in solar equivalent joules (SEJ) for each unit of output, measured in kg or J (Odum, 1998).

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[1] The first law of thermodynamic refers to the conservation of energy. It states that matter and energy can neither be created nor destroyed, only be transformed (Hussen, 2004).

In energy analysis, the boundary of a system starts with the primary energy resources and ends with the disposal of products, which is also called an LCA assessment (VDI 4600, ISO 14040 & ISO 14044). The emergy analysis quantifies all of the environmental flows and distinguishes the origin of each input (Zuberman, 2009). Additionally, the indicators used in the energy analysis measure the primary energy consumption in a process or product, whereas indicators used in emergy measure the whole energy flow of the process (renewable or non-renewable, commercial or non-commercial) and their contribution to the production energy (Odum, 1998 and Zuberman, 2009).

However, there are some disadvantages in the use of the exergy and the emergy methods, especially in agriculture. First, these methods make the analysis more complex. Second, physical work is not a desired energy output in agriculture. Finally, the desired type of work (e.g. electrical, mechanical, chemical) is not defined. Additionally, there is a large amount of energy input from the environment and the sun in agricultural systems. This input causes relatively low amounts of primary energy inputs to not be adequately considered. Therefore, in the boundary of these studies, solar energy is not taken into account, and only the commercial energy resources are investigated. In this study, the intended boundary of the system and energy analysis is based on the primary energy resources. The methodology is described below.

2.4 Energy analysis boundary

According to VDI 4600 and ISO standards (14040 and 14044), energy systems start with the consumption of primary energy and raw materials at the beginning of a process and end with the disposal of productions and necessary operations to remove the impacts of the process on the environment. This full LCA is also known as the cradle to grave assessment. Cradle refers to the resource extraction phase, and grave is indicative of the disposal phase.

As revealed in the VDI 4600 guideline (2012), CED consists of three parts of energy demand in each system: cumulative energy demand for production (CED_P), cumulative energy demand for use (CED_U) and cumulative energy demand for disposal of products and by-products (CED_D).

$$CED = CED_P + CED_U + CED_D \qquad \text{Equation 1}$$

In each part, the sum of the energy expenditures that result from the acquisition, processing, fabrication, transportation and disposal of used objects or services should be taken into account.

However, according to the purpose of the investigation, the proper boundary of any system and the estimated indicators could be redefined. In energy-agriculture and production of biomass crops (in replacement of food crops), the LCA methodology has vital importance. These systems have been introduced to replace non-renewable energy resources as a means to save the environment. Therefore, the entire system must be completely energy efficient (the energy output input ratio must be more than 1). In food production systems, some parts of LCA (e.g., disposal of products) are often neglected, and the investigation boundary is limited to the farm gate. This limited boundary is called cradle to gate assessment. This boundary can be extended to include the handling of products from farm, post-processing, packing, marketing, and finally, the disposal of all the materials used in these processes. Even though the aim of investigating the energy efficiency is to develop more efficient production systems, food production systems (i.e. livestock farming) are not expected to be absolutely energy efficient. In other words, the energy output should not be necessarily more than the energy input, even in the cradle to gate boundary. Figure 4 shows a diagram of material and energy flow during a production system.

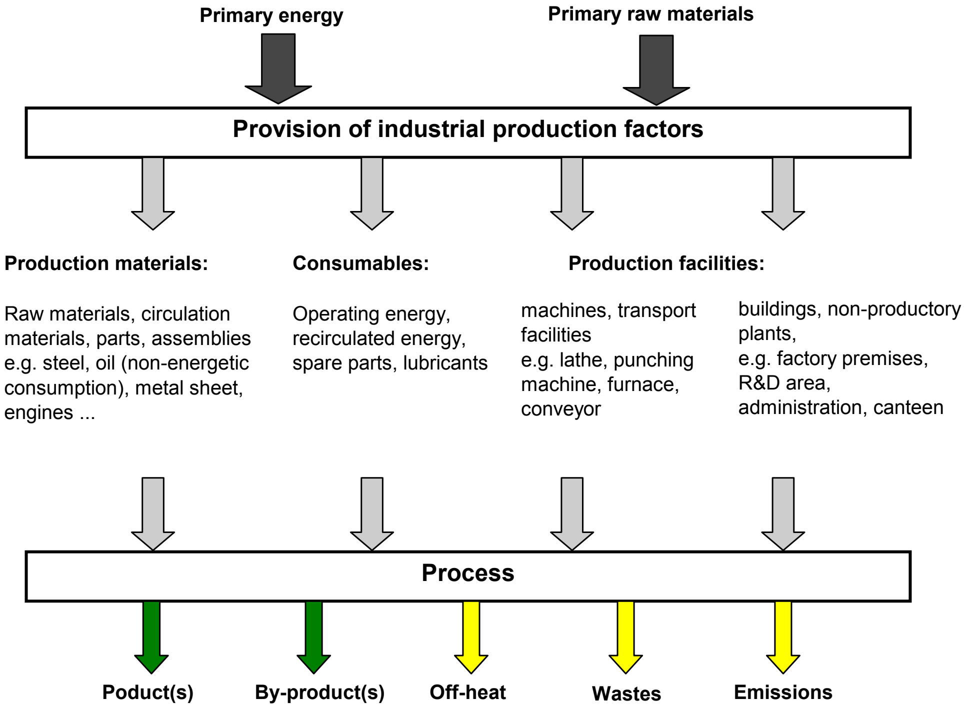


Figure 4 Diagram of material and energy process flows (VDI 4600, 2012).

To obtain a sense of the amount of energy input in each stage, IFIAS has suggested the following levels of energy consumption during each type of energy input in the mentioned boundary (Baird et al., 1997):

Level 1: Typically less than 50%:	Direct energy involved in the process only.
Level 2: Frequently approximately 40%:	Energy involved in extracting materials.
Level 3: Rarely greater than 1%:	Energy needed to make capital equipment.
Level 4: Usually very low:	Energy needed to make the machines that make the capital equipment.

2.5 Definition of terms

2.5.1 Definition of energy resource terms

Commercial energy: energy that is traded in the market and therefore has a market price. Coal, oil, gas and electricity are examples of commercial energy (Bhattacharyya, 2011).

Additionally, latent energy in biomass may belong to commercial energies, depending on the location. The availability to commercial energies is generally limited. Odum (1998) named this energy category ‘purchased energy’ in his emergy system diagram.

Non-commercial energy: energy that does not pass through the market and, thus, has no market price (Bhattacharyya, 2011). Environmental energies that have not been converted to commercial energy, such as wind, solar, water, and soil, belong to the non-commercial energy category.

Primary energy: energy that is found in nature and that has not undergone any conversion or transformation (other than separation and cleaning from attendant materials) (Bhattacharyya, 2011 and VDI 4600, 2012). Examples are coal, crude oil, natural gas, nuclear power, and solar energy.

Secondary energy: energy that is obtained through transformation and conversion of primary energy or some other secondary energy (Bhattacharyya, 2011 and VDI 4600, 2012). Examples are oil products and electricity.

Renewable energy: any primary energy that is obtained from a consistently available energy resource. Solar, wind and water flow are renewable energy resources (Bhattacharyya, 2011).

Non-renewable energy: a type of primary energy that comes from finite energy resources. Coal, crude oil, and nuclear are non-renewable energy resources (Bhattacharyya, 2011).

Direct energy input: energy input from primary or secondary energy resources that are consumed directly in a system or process. Examples are diesel, electricity, and gas.

Indirect energy input: energy input in the form of materials, facilities, or services that is equal to the primary or secondary energy resources consumed in their extraction, construction, transportation, and delivery. Energy input from machinery, building materials, and fertilisers are as examples of indirect energy input.

Final energy (end energy): energy content of all primary and secondary energy carriers that are ultimately available to the consumer. It is the net energy of the primary energies, reduced by conversion losses and auxiliary energy demand (VDI 4600, 2012).

Energy system: a chain of transformation and conversion processes and flows, where primary energy is processed until it reaches final energy and, thereafter, can be effectively used (product) (Orecchini & Naso, 2012).

Production energy: the sum of the energies consumed by an energy system during production until the product reaches the consumer.

Cumulative energy demand (Embodied energy): the entire primary energy demand that is consumed in a production process. With LCA methodology, the entire energy demand for production and disposal of production or any casual relation (VDI 4600, 2012).

2.5.2 Definition of heating values

Different heating values are defined based on different conditions and views. Depending on the purpose of consumption or study, heating specifications are defined and measured in various ways. To avoid of any confusion regarding thermal and energy statements, the precise definitions of heating values and energy content of investigated materials must be given. The values that are used or mentioned in this study are defined as follows:

Higher heating value (HHV): the maximum amount of heat produced by the complete oxidation and combustion of a given amount of material or fuel. The higher heating value is obtained when all products of the combustion, as well exhaust gases, are cooled down to the standard base temperature (or temperature prior to combustion) and all the produced or vaporised water during combustion is condensed (Kaltschmitt et al, 2009).

This value is calculated by assessing the combustion of materials or fuels in a bomb calorimeter. The higher heating value is also known as the gross caloric (or heating) value, upper heating value or superior heating value.

Lower heating value (LHV): the amount of heat produced by the complete oxidation or combustion of a given amount of a material or fuel, without considering the condensation heat of the produced or vaporised water (Kaltschmitt et al, 2009).

Engineers generally refer to this value as the practical combustion value of fuels needed to produce heat and energy. The lower heating value is also known as the net caloric value, lower caloric value or inferior caloric value.

The difference between HHV and LHV comes from the condensation energy of vaporised water during the combustion of materials. In completely water-free materials, there is a small difference between HHV and LHV, dependent on the chemical structure and amount of the produced water during combustion. This difference increases as the water content of combusted material or fuel increases (figure 5). The moisture content of materials also has a significant influence on the heating value. As shown in figure 5, the lower heating value of a biomass with moisture content of approximately 90% is zero.

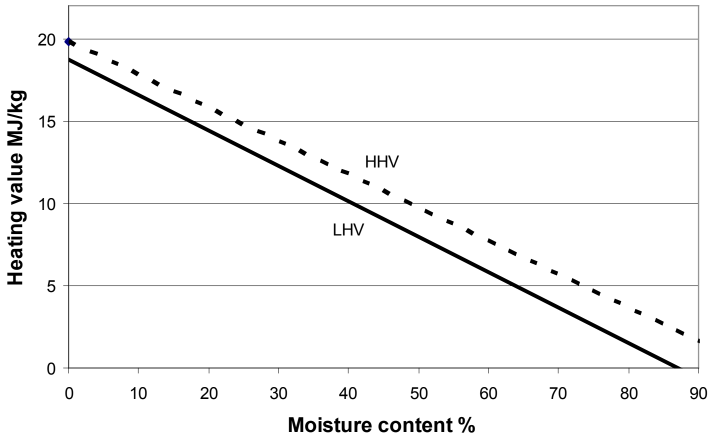


Figure 5 Difference between higher and lower heating value for most of biomasses (Kaltschmitt et al., 2009)

To convert the heating value from the dry matter-based value to the fresh matter-based value, two separate formulas are used. Converting the dry matter-based higher heating value (HHV_d in MJ kg^{-1}) to the fresh matter-based higher heating value (HHV_f in MJ kg^{-1}) with given moisture content (M) is described in equation 2:

$$HHV_f = HHV_d \times (1 - M) \qquad \text{Equation 2}$$

To convert the dry matter-based lower heating value (LHV_d in MJ kg^{-1}) to the fresh matter-based lower heating value (LHV_f in MJ kg^{-1}), equation 3 used as described by Kaltschmitt et al. (2009):

$$LHV_f = LHV_d \times (1 - M) - 2.443M \qquad \text{Equation 3}$$

Dependent on the aims of an energy analysis, the HHV or LHV of the consumed materials or fuels is used as the energy equivalent. However, in the animal sciences, other definitions are used to determine the energy content of feedstuffs because the higher heating value of feedstuffs is not completely used by animals. For example, the same amounts of straw and grain have nearly the same higher heating values, but the usable energy by animals from straw is not same as the usable energy from the grain (table 10). Therefore, other definitions were introduced for animal sciences as a means to quantify the energy content and qualify the feedstuffs. These definitions are as follows (from Kirchgeßner et al., 2008 and Moehn et al., 2005):

Digestible energy value (DEV): the part of the higher heating value of a feedstuff that is digestible by animals. It is the higher heating value of the feedstuff minus the higher heating value of the faeces, named the faecal energy.

Metabolisable energy value (MEV): the part of the digestible energy value that is not excreted during the metabolism of feedstuff through urine (urinary energy) or combustible fermentation gases (methane).

Net energy value (NEV): the energy that can be metabolised, minus the heat increment that is produced during the digestion of feed, nutrient metabolism and waste excretion.

Production energy value (PEV): the part of the net energy that is used for production (growth, gestation and lactation). Production energy is calculated as the net energy minus the energy used for maintenance.

Net energy lactation (NEL): the available energy in feedstuff for dairy cattle that is used for milk production and body maintenance. NEL is a special definition of NEV used in dairy cattle science.

These definitions indicate that only net energy is used by animals and that the difference between net energy and gross energy is actually the energy loss (Moehn et al, 2005). However, the maintenance energy is also energy loss, and only the production energy is converted to the target products, such as milk and meat (shown in figure 6).

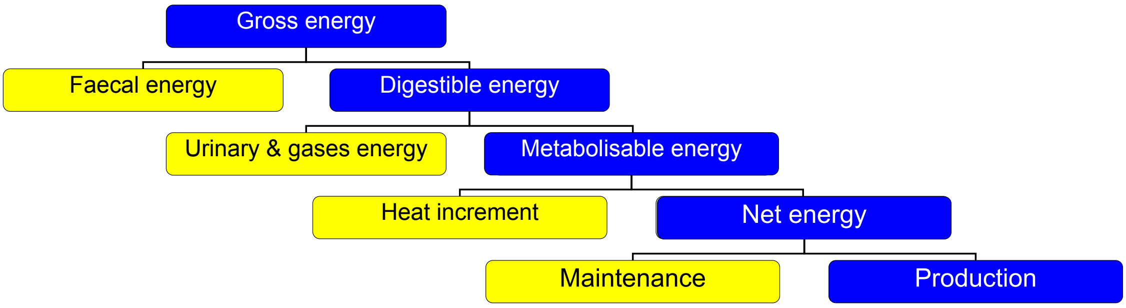


Figure 6 Energy losses from feedstuff in an animal body.

These energy values vary from animal to animal depending on the type and breed of the animal and are generally reported individually for ruminants, non-ruminants and poultry. Because many complexities and difficulties result when NEV is assessed, digestible (DEV) and metabolisable (MEV) energy values are widely used (Moehn et al, 2005), except in dairy cattle science, where NEL is widely used. Net energy lactation (NEL) is a more useful and specialised definition for determining the net energy used during the lactation of dairy cattle.

2.5.3 Definition of energy efficiency indicators

In general, energy efficiency refers to using less energy to produce the same amount of useful output (Patterson, 1996). Useful output of a process can be an energy output, a physical product, or a service (Patterson, 1996). To quantify the energy efficiency, different indicators, such as energy output/input ratio, energy productivity, energy intensity and net energy yield, have been defined and frequently used, especially in agricultural studies (Zuberman, 2009; Kuesters & Lammel, 1999). The most applied indicators in energy efficiency analysis are defined as follows:

Energy intensity (EI): the amount of final energy that is consumed to produce a unit of product. In agriculture, usually the unit of MJ kg^{-1} is used for this indicator.

This indicator is the most important indicator used for the indication of the efficiency of energy systems in the agricultural sector (IAEA, 2005).

In this study, the energy intensity (EI) corresponds to the cumulative energy demand (CED) concept and to the embodied energy (EE), which were defined previously. These terms are frequently used interchangeably in this study.

Energy productivity (EP): the amount of produced yield per a unit of final energy input. This indicator is the reverse of the energy intensity indicator and therefore has the unit of kg MJ^{-1} in agriculture.

Energy output/input ratio (OIR): the ratio of usable energy output to final energy input in a system. This indicator is the most famous and common indicator in energy efficiency analysis. Hence, this ratio indicates “energy efficiency’’. It is without a unit or can be referred to as MJ MJ^{-1}.

Net energy yield (NEY): the difference between the usable energy output (yield) and the energy input. The unit of this indicator is MJ. This indicator is sometimes called the “net energy gain”.

Labour energy productivity (LEP): the amount of produced energy per hour of labour. The unit of this indicator is MJ h^{-1} of labour work.

The first two indicators are a combination of physical and thermodynamic specifications. In regard to these indicators, the more efficient system uses less energy to produce a unit of production or service. The use of a physical unit of output in these indicators helps to evaluate a production system or service delivery system without any difficulties that might occur when converting the output to energetic units. Additionally, the consumer or producer do not evaluate the end product or service based on a heat content or work potential basis, but can still objectively compare the product. However, in the case of the existence of several products or by-products, an allocation issue will arise (Patterson, 1996).

The next two indicators reveal the difference between the heating or energetic value of inputs and useable outputs of a system. According to these indicators, the more efficient system is the one that converts more input energy (in any case) to usable output energy.

The last indicator is defined by own, because the importance of labour work must be addressed due to the reduction of its availability and increasing wages, especially in agriculture. More energy production per hour of labour work is one of the aims of agricultural research. LEP does not directly indicate the energy efficiency of a system and seems to be related to the mechanisation status of a system. However, in addition to the other indicators, it contributes to an extended interpretation of the efficiency of the systems.

2.6 Energy input equivalents

Energy input into a system is in the form of direct energy and indirect energy. Direct energy is in the form of primary energy resources, such as crude fossil oil, gas, coal and nuclear power, and secondary energy resources, such as electricity, human and animal works, and even diesel and other refinery products of fossil fuels, which are the converted or modified forms of primary energies. Indirect energy is the energy embodied in facilities and services used in the production.

According to VDI Guideline 4600, all direct and indirect energy inputs should be included in assessments (VDI 4600, 2012). However, depending on the aim of the assessments, some of the energy inputs may be neglected by limiting the boundary of the investigation. Therefore, there is a need to clearly define all included and excluded energies in the analysis to avoid diversity in the methodologies, thereby resulting in data that are comparable.

In energy analysis, the environmental energy resources, such as passively utilised solar energy (air, soil and water temperature (VDI 4600, 2012)), wind energy, latent energy in soil, and hydro-power, are not taken into consideration, with the exception of the energy consumed for their transport and supply. In general, all of the energy resources that are not in the list of commercial energy resources are excluded. Moreover, because of uncertain or missing data, some energy inputs (especially in infrastructures) may be included through a rough estimation.

All energy input calculations are based on the whole fuel cycle, including the primary energy need for producing the energy carrier used as both raw material and fuel. The higher heating value of primary energy resources is the basis of energy content (Börjesson, 1996). According to this concept, energy efficiency is actually the efficiency of the primary energy resources. The higher heating value would be more appropriate for describing the energy content of resources and materials, with the exception of the energy of other combustible materials that are not registered as energy carriers in the national energy statistics, such as biomass (VDI 4600, 2012). VDI guidelines recommend the lower heating value for biomass (see 2.6.2.6.2). For different sites and conditions, the conversion of primary energy efficiencies to secondary energies or to indirect energy resources can vary significantly. Therefore, depending on specifications of the regions, different energy equivalents for the same input is possible and should be considered.

2.6.1 Direct energy

Energy input from direct energy resources is calculated by multiplying the consumed amount of the energy resource by its energy equivalent. The following are common direct energy resources in agriculture:

2.6.1.1 Electricity

The energy of electricity in the primary energy-based analysis is the energy embodied in the life cycle of electricity production, which should be used in the calculation of the energy input. The amount of energy embodied in electricity production in each country depends on the structure and fuel composition of its power plants. An average demand of 12.0 MJ per kWh is reported by Ortiz-Canavate and Hernanz (1999) which is the energy embodied in its production (8.4 MJ kWh^{-1}) in addition to its secondary energy value (3.6 MJ kWh^{-1}). The share of renewable energy is not reported, but it can be assumed that this share is small and therefore not relevant to the end results. According to CED, only the production energy should be used as the electrical energy equivalent what that is used in this study.

2.6.1.2 Fuels

The energy input from the direct consumption of fuels includes the energy content of fuel in the base of HHV, in addition to the energy embodied in its production, such as the energy consumed in mining, excavation, refinery and transportation. Indirect energy embodied in fossil fuel production was assumed by Börjesson (1996) to correspond to 10% of the energy content of the fuels. Furthermore, another 4% of the energy content of diesel corresponds to energy input in the form of lubricants. Therefore, with a HHV of 38.7 MJ l^{-1}, Börjesson presumed that the energy input from diesel consumption was 44.3 MJ l^{-1}. Table 3 shows the energy equivalent of various energy resources reported by Ortiz-Canavate & Hernanz (1999).

Table 3 Energy equivalent of fuels in MJ per unit (Ortiz-Canavate & Hernanz, 1999)

Energy resource	*Unit*	*HHV* [a]	*Consumed energy in production*	*Total energy equivalent*
Gasoline	l	38.2	8.1	46.3
Diesel	l	38.7	9.1	47.8
Fuel oil	l	38.7	9.1	47.8
LPG [b]	l	26.1	6.2	32.3
Natural Gas	m^3	41.4	8.1	49.5
Coal	kg	30.2	2.4	32.6
Electricity	kWh	-	8.4	12.0

[a] Higher heating value; [b] Liquid petroleum gas;

Fuel consumption of machinery

To calculate the fuel consumption of a machine, several methods are used. Factories, researchers and agricultural engineering associations have introduced various theoretical formulae to calculate the fuel consumption of tractors and self-propelled agricultural machineries. Another method uses empirical data adapted to different agricultural machinery operations (table 4). These equations or tables are based on the specifications of the engine, implement, and soil and estimate the fuel consumption of a machine per hectare or per hour of operation. However, due to many factors affecting machinery operation, such as weather, soil, depth of work, field shape and size, and particularly managerial factors, both of these methods may not determine the fuel consumption of different machinery in different sites precisely. For example, a fuel consumption rate of 17.5 and 24.2 litre per hectare for mouldboard operation was recorded in two different regions (Bowers, 1992) that are very different. The field measuring techniques, such as fuelling the tank before and after the operation or use of measuring instruments, can estimate the fuel consumption more accurately than use of theoretical data (Fathollahzadeh et al., 2011). Fuelling and refuelling the tank before and after the operation introduces some errors (Fathollahzadeh et al., 2011), but it is the simplest way to measure farm fuel consumption that is practiced by the farmers. Fuel consumption should include all consumption between the entrance and the exit of the machinery from the field, in addition to the transportation of the machinery between farms.

Table 4 Diesel consumption in farm operations estimated by Ortiz-Canavate & Hernanz (1999)

Operation	*Consumption (l ha^{-1})*	*Operation*	*Consumption (l ha^{-1})*
Mouldboard plough	25±7	Centrifugal fertilizer	2±0.5
Disc plough	22±5	Manure spreader	7±2
Chisel (straight arm)	13±2	Mounted sprayer	1.5±0.5
Chisel (curved arm)	10±2	Trailed sprayer	3±0.5
Heavy disc harrow	9±3	Grain drill	5±0.5
Medium disc harrow	7±2	Row planter	5.5±1
Heavy cultivator	10±2	Ridge planter	17±1.5
Light cultivator	8±1	Combine	18±2
Vibro-cultivator	6±1	Cutterbar mower	4±0.5
Rotary hoe	4±1	Rotary mower	5.5±0.5
Roller	4±1	Swather	3±1
Rotary cultivator	20±4	Baler	5±1
Hoeing toolbar	2±0.5	Forage harvester	25±5
Combined equipment for ploughing - seedbed preparation	24±6	Sugar beet harvester	60±10

2.6.1.3 Human

In several studies, such as Ozkan et al. (2004b), human work was included in the energy analysis as an energy input resource, with an equivalent of 1.96 MJ h^{-1}. However, according to VDI Guideline 4600 and Pimentel et al. (1983), no energy input from labour is considered in energy analysis.

Energy input from labour could be categorised as secondary direct energy input. However, it is hard to clearly define an exact relationship between the energy embodied in human food and the energy produced in the human body or the energy used for physical work.

Regarding the claimed energy equivalent to human work, the share of the energy input by human work in the total energy input into the farm is insignificant. It is reported by Ozkan et al. (2004b) to be 2.6% of the total energy input for an orange farm, and by Maysami et al. (2009) to be between 0.5% and 2.1% for wheat cultivation and 4.6% for onion cultivation, where more labour work for weeding is required. These low shares did not include labour energy in the energy analysis, while in most cases, human labour is a high value input due to its availability and cost. Therefore, other indicators could be applied to investigate a system based on its labour requirement. Pimentel et al. (1983) used labour productivity or produced yield per one hour of labour work to assess production systems. This indicator could be redefined as the amount of energy produced per one hour of labour work or labour energy productivity (LEP).

2.6.2 Indirect energy

Indirect energy input includes a vast range of materials or services used and consumed in a system or infrastructural facilities, such as transportation systems, massive irrigation and drainage systems, and delivery networks (electricity, water, and communication). As a result of daily innovations and progress in converting processes, embodied energy in materials and services is changing rapidly. Increasing energy efficiency causes embodied energy to decrease, while more complex systems and materials result in higher embodied energy. For this reason, frequent updates in the calculations of energy equivalents of indirect energy resources are needed. Some of the most important indirect energy input resources in agricultural systems are reviewed in more detail in the following sections.

2.6.2.1 Machinery

The first investigation of indirect energy consumption in machine production was performed in 1972 by Berry and Fulton Fells on automobile manufacturing. Their study indicated that 81.2 MJ kg^{-1} of automobile is consumed energy in automobile manufacturing (Mikkola and Ahokas, 2010). Pimentel et al. (1973) modified this research for agricultural machinery and presented an embodied energy of 86.8 MJ kg^{-1} of agricultural machinery from the cradle to the gate of the factory. In 1980, Pimentel modified his methodology to calculate the energy embodied in agricultural machinery to include the energy embodied in the materials for the parts, the fabrication of parts and spares, and the energy to assemble the parts (cited in Börjesson, 1996).

Embodied energy in machinery is categorised in four steps. First, the energy embodied in the raw materials is assessed. Second, the energy used in processing the raw materials and part production and the energy used in assembling the parts are determined. Third, the energy consumed in the transportation and distribution of machinery is calculated. Finally, the energy embodied in the repair and maintenance, including spare parts and services, is considered. Only a small portion of farm machinery is recovered and recycled as scrap metal. Therefore, the energy consumed in the disposal is neglected by most authorities (Bowers, 1992). Scholz et al. (1998) estimated the energy demand for the disposal of agricultural machinery to be 0.5 MJ kg^{-1}.

Tractors are made of heavy parts of cast iron, whereas the body of a car is generally made of steel sheet. The use of synthetic materials in cars has increased, and the tyres, fuel tank, cabin and bonnets of tractors have also recently been made of plastics and fibreglass (Mikkola and Ahokas, 2010). The energy consumed in material production has been reduced during the last few decades. As reported by Börjesson (1996), American steel production consumed 63 MJ kg^{-1} in the late 1970s, while this value was 24 MJ kg^{-1} in the 1990s in Sweden, with an assumption of a further 30% energy reduction in following two decades. Energy input per kg material is two times more in steel production than that in cast iron production, but is 4 times less than that for rubber production (Börjesson, 1996). Börjesson claimed that tractors and forestry machines are made of 45% steel, 45% cast iron and 10% rubber or plastic, while implements are often made from steel. Thus, the energy input per kg of tractor material should be similar to the energy input per kg of steel. However, Mikkola and Ahokas (2010) claimed that the use of more sophisticated complexes and more energy intensive materials, such as plastics and aluminium, in recently manufactured tractors suggested that the energy analysis of agricultural machinery should not be made on the basis of energy consumption in steel production. So far, there is no comprehensive analysis of the energy intensity in car manufacturing, agricultural machinery manufacturing and the structural differences between them (Mikkola and Ahokas, 2010).

The determination of consumed energy in machinery manufacturing is a very time-consuming and onerous part of machinery energy calculations. Because machines consist of diverse parts of different materials made in different firms and sub-factories, it is difficult to acquire information about them. Table 5 shows the energy consumption estimations in the manufacturing of farm machinery from Bowers (1992) and Börjesson (1996).

Table 5 Energy consumption during the manufacturing of farm machinery (excluding energy embodied in materials), given in MJ kg^{-1} machinery.

Machinery	*(Bowers, 1992)*	*(Börjesson, 1996)*
Tractor	27.63	11
Combine	21.65	9.1
Plough	12.78	6.3
Disc	9.96	5.9
Applicator	10.20	5.1
Planter	16.90	5.1
Rotary hoe	11.38	5.9
Mower, baler and harvester	-	4.8
Other	-	5.1

Bowers (1992) revealed that a simple way to estimate the energy embodied in agricultural machinery is to use the 86.77 MJ kg^{-1} value (estimated by Pimentel et al. in 1973) as the energy embodied in the assembled machinery (from the cradle to the gate of factory). This estimation includes the tyres because the suggested embodied energy value for tyres (85.8 MJ kg^{-1}) by Doering et al. (1977) is close to the energy embodied in the assembled machinery estimated by Pimentel et al.. Therefore, tyres can be considered a part of the manufactured machine. In 1983, Yisheng estimated a consumed energy value of 209 MJ kg^{-1} for machinery production in China, which was two times more than that in the USA. It seems that this difference was due to smaller and less efficient manufacturing companies (Bower, 1992).

Consumed energy during the transportation of machinery from the factory to the farm depends on the distance between the two locations and the transportation system. Bowers (1992) estimated an additional energy demand of 8.8 MJ kg^{-1} of machinery for transportation and distribution of manufactured products. Börjesson (1996) made an assumption of 10% of energy embodied for assembled machinery for transportation. With an embodied energy of 86.77 MJ kg^{-1} for assembled machinery (Pimentel et al., 1973), the results of both estimations are quite similar.

Authors differ in respect to their calculations of energy embodied in repairs. Repair and maintenance (R&M) also has a significant share of the indirect energy of machinery (Bowers, 1992). Because of the lack of information on repair and maintenance, it is difficult to clearly determine the energy embodied in R&M. Information is needed on the accumulated mass, materials and frequency of spare parts; facilities, such as storage buildings; tools and instruments used in repair and maintenance of the machine during its service life and also service and activities made by dealers, farmers and workshops. According to the total accumulated repair costs, Pimentel used a formula to assume the energy embodied in R&M. However, the investigation of Börjesson (1996) showed that the results of that formula were 50% too low. Mikkola and Ahokas (2010) reviewed some recent research on the R&M of cars and agricultural machineries, which all showed different ratios for the energy embodied in R&M to the energy embodied in assembled machinery. These reported values were between 6 percent for tractors by Pimentel et al. in 1973 to 360 percent for cutter bar mowers by Fluck and Baird in 1985 (cited by Mikkola and Ahokas, 2010). These estimations were generally based on monetary models that were driven normally from accumulated repair cost models or part producers and sellers statistics (Börjesson, 1996). The changes in the prices, the different results of the models and some ignored data in the models caused high variation in the results. For example, as cited by Bowers (1992), in the research of Fluck and Baird, 55% of the energy embodied in assembled machinery was needed for R&M when it was based on the industry cost model; it was 138% when based on the lifetime machine repair cost model. Bowers (1992) estimated the energy sequestered in R&M as a ratio to the energy embodied in assembled machinery. In his estimation self-propelled combines had the lowest ratio while, for cutter bar mowers had the highest, at 1.44. On average, for 14 machines the ratio was 0.55, which is the same ratio estimated by Fluck and Baird with the industry cost model (Bowers, 1992). The average R&M ratio used by Börjesson (1996) was 0.75, which is 36% higher than those estimated by Bowers (table 6).

Assuming the value of 86.77 MJ kg^{-1} of machinery for the embodied energy in assembled machinery, including the tyres, 8.8 MJ kg^{-1} of machinery for transportation and distribution, and the R&M ratios estimated by Bowers (1992), the energy embodied in different farm machinery are shown in table 6. Bowers revealed that the size of the machine (for example, two types of combine) has very little effect on the energy input for a given amount of area by the embodied energy in the machine.

The allocation of the indirect energy embodied in machinery to the biomass production is also an issue. Machinery energy (ME) input is generally calculated in MJ per hour of machinery work, as shown in equation 4 (Ozkan et al., 2004), where G is the machine mass, E is the energy equivalent of each kg of machine, and T is the machinery lifetime (mentioned in the table 6).

$$ME = G \times E/T \qquad \text{Equation 4}$$

With a given or assumed duration of operation per area, the indirect energy input per area is calculated in MJ per hectare.

With a given or assumed operated area (ha) during the machinery real lifetime, the embodied energy in the machinery is divided into the total operated area (equation 5).

$$ME = G \times E/ha \qquad \text{Equation 5}$$

There can be significant differences between the real and calculated machinery lifetime. If no real data are available, calculated values have to be used. ASABE standards give 12,000 hours of lifetime to 2-wheel drive tractors, while the average annual usage of tractors was 200 h per year in Denmark, 200-600 h per year in Canada and 300 h per year in the USA (Mikkola and Ahokas, 2010). These values mean that with an estimated economic life of 10-15 years, the total tractor usage is between 2,000-9,000 h. Furthermore, in this method, there is no difference between light usage of the tractor in a one hour operation, such as spraying, and one hour of heavy operation, such as ploughing. Mikkola and Ahokas (2010) have described a method that could overcome this disadvantage. In this method, indirect energy is incorporated with fuel consumption during each operation. Thus, with high fuel consumption during a heavy operation, a higher share of indirect energy is considered in this operation. In this method, the total indirect energy embodied in a machine is divided into the total fuel consumed in the real service life of the machine, and the result is added to the direct energy of the fuel. The difficulty of this method is in the exact estimation of the total fuel consumption and the real service lifetime of the machine.

Table 6 Embodied energy in farm machinery (MJ kg^{-1}) and machinery lifetime (h).

Machinery	*Ratio of R&M [a] to embodied energy in assembled machinery*		*Total embodied energy [b] (MJ kg^{-1})*	*Lifetime [c] (h)*
	(Börjesson, 1996)	(Bowers, 1992)		
Tractor	0.82	0.49	138.1	
2-Wheel drive				12,000
4-Wheel drive				16,000
Self-propelled combine	0.46	0.24	116.4	3,000
Mouldboard plough	0.93	0.97	179.7	2,000
Planters	0.76	0.43	132.9	1,500
Row cultivators	0.93	0.58	145.9	2,000
Field cultivators	0.93	0.51	139.8	2,000
Disc harrows	0.93	0.61	148.5	2,000
Corn pickers	0.61	0.35	125.9	2,000
Stalk choppers	0.61	0.33	124.2	2,000
Cutterbar mowers	0.61	1.44	220.5	2,000
Balers	0.61	0.39	129.4	2,000
Forage harvesters	0.61	0.39	129.4	2,500
Rotary hoes	0.93	0.59	146.8	2,500
Fertilisers and sprayers	0.76	0.37	127.7	1,200 - 1,500
Average	0.75	0.55	143.2	-

[a] repair and maintenance; [b] includes materials, manufacturing, transportation, and repair and maintenance based on Bower's ratios; [c] from ASABE D497.6 (2009)

2.6.2.2 Buildings

Buildings in agriculture include barns, storage, machinery hangars, and other facilities used as labour houses or workshops. There is a wide variety of construction materials used in these buildings, in addition a difference in the lifetimes of the buildings. These variations make it difficult to accurately calculate the energy embodied in the buildings. The allocation of the embodied energy to the unit of production is also an issue. Because of the low share of energy from workshops or hangars in the production energy of agricultural commodities, it is generally neglected. The determination of the main structural materials of a building and the energy consumed in material production (primary energy based) allow for a rough estimation of the embodied energy in the buildings. By estimating the volume of the materials used, the density of the materials used described in engineering handbooks, and the energy equivalents (table 7), the energy embodied in the building construction can be calculated. With an assumption of a lifetime of 25 years for buildings (Kraatz, 2012), the allocation of this energy to the unit of production delivers values that are high enough to be included in the final consideration of the energy analysis. This share in dairy cattle farming in Germany was calculated as 3% of all of the energy embodied in the milk production (Kraatz, 2012). In table 7, the energy equivalents of some materials are shown based on the German GEMIS data base (GEMIS, 2006) and New Zealand statistics (Baird et al., 1997).

Table 7 Energy equivalents of building materials.

Material	*Energy equivalent* *MJ kg^{-1}* *(GEMIS, 2006)*	*Energy equivalent* *MJ kg^{-1}* *(Baird* et al.*, 1997)*	*Density* *g cm^{-3}*
Steel	20	32	7.9 [a]
Stainless steel	103	-	8.0 [b]
Plastics (PVC, Rubber, PP)	87 - 110	54 - 117	0.9-1.5 [a]
Glass	15	15.9	2.5 [a]
Concrete	0.8	1	2.2 [a]
Reinforced concrete	1.2	2	2.4 [b]
Wood	0.1	0.3	0.45 [a]
Fibreglass	15	30	1.5 [b]
Brick	2.7	2.5	1.8 [b]
Aluminium	191	191	2.7 [a]
Bitumen	43	44.1	1.0 [b]
Zinc-plated sheet	36	35	7.1 [b]

[a] ECOINVENT (2007); [b] The engineering toolbox (2012),

Another way to estimate the energy embodied in buildings is through the use of standard calculations defined in the building construction for standard houses. Baird et al. (1997) presented the calculated embodied energy in different types of buildings, which is shown in table 8.

Table 8 Embodied energy in standard buildings (Baird et al., 1997)

Wall	*Roof*	*Floor*	*Embodied energy GJ m^{-2}*
Weatherboard	Concrete tile	Particle board	0.7
		Concrete slab	0.9
	Corrugated galvanised	Particle board	0.9
		Concrete slab	1.1
Concrete masonry	Concrete tile	Particle board	1.3
		Concrete slab	1.4
	Corrugated galvanised	Particle board	1.4
		Concrete slab	1.6
Brick veneer	Concrete tile	Particle board	1.1
		Concrete slab	1.2
	Corrugated galvanised	Particle board	1.3
		Concrete slab	1.4

2.6.2.3 Fertilisers

One of the main factors in increasing food production is the use of fertilisers. The consumption of fertilisers causes a high-energy input on a farm because fertiliser production is a high-energy-consuming process, especially for nitrogen fertiliser. In fertiliser production, there are different production processes all over the world, using modern or older technologies, which result in lower or higher energy consumption, respectively. In some energy analyses, the LHV is used instead of the HHV, or the secondary energy is used instead of the primary energy, especially for electricity energy (Mudahar and Hignett, 1985).

Nitrogen (N) fertiliser is the most energy-intensive fertiliser because of the consumption of natural gas as both feedstock (82%) and fuel (18%) in its production (Jenssen, 2003). N fertiliser production is approximately 9 times more energy intensive than phosphate and 11 times more energy intensive than potash fertiliser production (Mudahar and Hignett, 1985). In the energy analyses of agricultural products, a wide range of 39 to 78 MJ kg^{-1} is used as the embodied energy in N fertiliser, which makes it difficult to compare the results across studies. Therefore, it is necessary to review the energy flow in the N fertiliser production process to find the best fitted energy equivalent to this fertiliser.

The most common N fertilisers are urea, ammonium nitrate and ammonium sulphate, in which the share of urea is highest. The basic feedstock in N fertiliser production and the most energy-consuming production is ammonia. The worldwide average energy input per kg of NH_3 production is 36.6 MJ (44.4 MJ kg^{-1} N) (IFA, 2009). To produce urea from ammonia, 9.0 MJ kg^{-1} NH_3 (10.9 MJ kg^{-1} N) on average is consumed in European plants (Jenssen, 2003). Furthermore, energy is consumed in the packaging, transport and delivery of the fertiliser to the market, which was estimated to be near 8.7 MJ kg^{-1} N (Helsel, 1992). Therefore, an embodied energy of 78.2 MJ kg^{-1} N fertiliser, reported by Helsel (1992) and Ortiz-Canavate & Hernanz (1999) and cited by Gellings and Parmenter (2004), seems to be the most precise world average (see table 9).

Table 9 Embodied energy in chemical fertilisers (Helsel, 1992)

	Nitrogen *MJ kg^{-1} N*	*Phosphate* *MJ kg^{-1} K_20*	*Potash* *MJ kg^{-1} P_2O_5*
Produce	69.5	7.7	6.4
Package	2.6	2.6	1.8
Transport	4.5	5.7	4.6
Apply	1.6	1.5	1
Total	78.2	17.5	13.8

2.6.2.4 Pesticides

According to the active substance in pesticides, primary energy consumption in production, formulation, packaging and delivery for the 50 most used pesticides varies between 107 MJ kg^{-1} of 2-4D (Herbicide) and 713 MJ kg^{-1} of Boscalid (Fungicide), as reported by Audsley et al. (2009). These values are estimates from data from the last 20 years and may include errors (Audsley et al., 2009). Production processes are becoming more efficient, but conversely, chemical formulas have become more complex and hence, more energy consuming (Audsley et al., 2009). Pesticides are a mix of active substances and inactive peripheral substances. Pesticides are usually not known and are not reported with active substance names, rather, they are reported by their commercial names. In most references, an average value is reported for the energy embodied in commercial pesticides. Rathke & Diepenbrook (2006) have used 237, 288 and 196 MJ kg^{-1} active substances as the energy equivalents of insecticides, herbicides and fungicides, respectively.

2.6.2.5 Irrigation

The energy input for irrigation and water supply depends greatly on the delivery systems. Corresponding to the LCA method, the direct and indirect energy consumed in the construction, maintenance, operation and decommissioning of entire facilities (which may include dam, channels, land preparing, pipelines, and water pumps), should be taken into account. There are very few studies applying LCA to different irrigation systems. Furthermore, in the existing reports, the full life cycle of the systems has not been analysed (Jacobs, 2006). In some studies, the consumed energy has been calculated by the use of standard equations governing the operation of electric or internal combustion motors. Alexandrou et al. (2009) calculated the direct energy consumption of a sprinkler irrigation system with addition of an extra 18% to cover the indirect energy inputs. Ozkan et al. (2004b) used a value of 0.63 MJ m^{-3} water to calculate the energy input from irrigation, but without determining the irrigation system. Another assay was aimed at the consideration of the entire life cycle of different irrigation systems in Australia, but the construction of water storage, such as dams, was not included (Jacobs, 2006). An average of 0.46 MJ m^{-3} water for a border-check irrigation system (flooding) was derived through the study of Jacobs.

2.6.2.6 Biomass

The determination of the energy input in the form of biomass to a system is conducted in many different ways and, thus, leads to varied results across studies. Different equivalents can be considered as energy inputs from biomass to a system. Regarding a common way to considering the energy input from other inputs, some researchers, such as Börjesson (1996) and Pimentel et al. (1983), try to keep the same methodology and use the higher heating value of biomass plus the energy embodied in its production as the energy equivalent of biomass. Kuesters and Lammel (1999) used only the energy embodied in seed production. On the other hand, VDI guideline 4600 (2012) introduced the use of the LHV for combustible materials (e.g. biomass) that are not used as energy. Another method is the use of more specialised energy specifications, such as metabolisable energy value (MEV) or net energy lactation (NEL) of biomass in animal husbandry systems, where materials are not used for physical combustion, but as feedstuffs.

2.6.2.6.1 Investigation scenarios

Due to the different energy equivalents of materials that are used for purposes other than energy resources but that can also be used as energy resources, there are significant differences between studies. In animal husbandry systems, where most of the energy input is from feedstuffs, assigning a proper equivalent is more important. According to the chosen energy efficiency indicators in an energy analysis study and the interpretation of useful biomass output in that study, five possible scenarios are defined as follows:

In CED theory, the main reason to investigate the energy efficiency of any system is to determine its dependency on non-renewable energy resources (fossil fuels). The energy intensity (EI) is the main efficiency indicator used for this purpose. Therefore, the first scenario is named in this study as EEV basis scenario and defined as:

A) The energy equivalent of each input, as well as the biomass, is equal to the non-renewable energy consumed directly and indirectly in its production. The outputs are not converted to an energy value.

Although in VDI guideline 4600 the LHV was introduced as the energy input from biomass, only the non-renewable energy embodied in the production of biomass should be used but regarding to the general theory of this guideline. However, considering the energy of biomass as a potential energy asset, the use of the LHV of biomass in assessments is reasonable. Thus, scenario B is deducted from scenario A as:

B) The energy equivalent of biomass corresponds to its LHV. The energy equivalent of all other inputs is equal to the non-renewable energy consumed directly and indirectly in its production. The outputs are not converted to an energy value.

Agricultural residues that are used in bio-energy systems are examples of biomass energy assets. The reason for using the LHV of biomass instead of the HHV in this scenario is that in conventional systems, the LHV of biomass is generally obtained.

In nutrition sciences as well as in this study the caloric value (HHV) is used to credit biomass. Therefore, scenario B could be rewritten for nutrition science as:

> The energy equivalent of biomass corresponds to its HHV. The energy equivalent of all other inputs is equal to the non-renewable energy consumed directly and indirectly in its production. The outputs are not converted to an energy value.

To investigate the energy efficiency of a system by means of the energy output/input ratio (OIR), the output must be converted to an energy value. In regard to this, scenarios C and D are defined as below:

C) The energy equivalent of each input, as well as the biomass, is equal to the non-renewable energy consumed directly and indirectly in its production. The energy equivalent of useful outputs, as well as biomass, is equal to its HHV (or LHV).

D) On both the input and output sides, either the HHV (or LHV) of biomass is used as the energy equivalent of biomass.

Another observed scenario, used by Börjesson (1996) and Pimentel et al. (1983), is the use of the HHV (or LHV) of biomass plus embodied energy in its production as energy input from biomass consumption. This scenario is as below:

E) The HHV (or LHV) of biomass plus embodied energy in its production is used as energy input from biomass.

2.6.2.6.2 Biomass energy content

In food and feed production systems, the HHV is used as the heating value and is generally called the caloric value. The dry matter HHV is the most reported thermo-physical specification of biomasses in databases. Therefore, the use of dry matter as the basis for input and output biomasses in an energy analysis makes it easier to compare the results of different studies. However, it is possible, and sometimes more useful, to use other energetic values of biomasses to make a more specialised investigation of biomass production. These values can be the DEV, MEV or NEL, which are used as the energetic values of feedstuffs in animal husbandry.

Energy content and heating value of biomass depends on its composition. The share of fat, protein, carbohydrate, fibre, amino acids, and ash, in addition to other components and elements, has an influence on the heating value or feeding values of biomass. The same type of biomass could have different energy content, resulting from different growing conditions or varieties. This difference is normally not significant. In table 10, the energy content of biomasses used as cattle feed are shown.

Table 10 Energy content of typical biomasses used as cattle feedstuff (in MJ kg^{-1} DM).

Biomass	*Moisture* % [a]	*HHV* [b] MJ kg^{-1}	*LHV* [b] MJ kg^{-1}	*DEV* [b] MJ kg^{-1}	*MEV* [b] MJ kg^{-1}	*NEL* [b] MJ kg^{-1}
Alfalfa fresh	79 [c]	18.1 [d]	17.4 [e]	11.8 [d]	9.3 [c]	5,4 [c]
Alfalfa hay	10 [f]	18.2 [d]	17.4 [e]	10.9 [f]	8.2 [f]	5.0 [f]
Barley grain	11 [f]	18.4 [d]	17.0 [g]	15.2 [f]	12.2 [f]	7.8 [f]
Barley straw	12 [c]	18.3 [d]	17.2 [g]	9.0 [i]	6.8 [d]	3.8 [c]
Beet (sugar beet)	77 [c]	17.2 [d]	16.0 [h]	14.9 [d]	12.6 [c]	8.0 [3]
Beet pulp	12 [f]	17.0 [d]	16.4 [g]	13.7 [d]	11.2 [d]	7.2 [j]
Beet molasses	22 [f]	15.5 [d]	14.7 [h]	15.1 [f]	12.0 [f]	7.7 [f]
Cottonseed (with linter) [k]	10 [f]	23.8 [d]	22.1 [h]	17.7 [k]	16.0 [k]	9.3 [k]
Cottonseed hulls (as well gin trash)	11 [f]	19.7 [d]	18.3 [h]	8.3 [l]	7.3 [d]	4.2 [l]
Cottonseed meal (41% protein) [k]	10 [f]	21.2 [d]	19.8 [h]	14.9 [k]	13.0 [k]	7.7 [k]
Fat (palm oil [m])	0 [m]	37.9 [i]	36.7 [h]	36.0 [i]	34.3 [m]	24.3 [j]
Fishmeal	9 [f]	20.9 [n]	20.2 [h]	17.7 [f]	13.6 [d]	7.6 [j]
Maize corn	12 [f]	18.7 [d]	17.4 [g]	16.1 [f]	13.1 [f]	8.4 [f]
Maize silage	65 [o]	19.0 [d]	17.7 [g]	13.0 [d]	10.7 [c]	6.4 [o]
Meat and bone meal	6 [f]	16.7 [d]	15.5 [h]	13.3 [f]	10.6 [f]	6.8 [f]
Poultry offal	8 [d]	22.7 [p]	21.1 [h]	17.5 [d]	15.7 [p]	7.7 [l]
Rapeseed (40% oil [g])	12 [c]	31.5 [g]	26.5 [g]	23.4 [f]	17.5 [c]	10.7 [c]
Rapeseed oil	1 [q]	39.4 [g]	36.0 [g]	-	30.0 [q]	19.3 [q]
Rapeseed meal	9 [i]	21.8 [p]	20.3 [h]	16.8 [d]	13.1 [d]	7.4 [r]
Soya bean (20% oil [d])	12 [c]	23.2 [n]	21.6 [h]	19.8 [d]	15.9 [c]	9.9 [c]
Soya bean meal (44% protein)	11 [f]	19.7 [d]	18.5 [h]	16.9 [f]	13.8 [f]	8.9 [f]
Sunflower seed (36% oil [d])	8 [f]	32.6 [n]	30.3 [h]	22.5 [f]	19.7 [f]	14.1 [f]
Sunflower meal dehulled	8 [f]	19.3 [d]	17.9 [h]	12.7 [d]	9.6 [d]	7.3 [j]
Tomato	93 [d]	18.2 [d]	17.0 [h]	12.7 [s]	-	6.6 [s]
Pomace dried (10% of tomato [d])	75 [f]	21.8 [d]	20.3 [h]	12.5 [f]	9.9 [f]	6.4 [f]
Wheat grain	11 [f]	18.2 [i]	17.0 [g]	16.0 [f]	13.0 [f]	8.3 [f]
Wheat bran	11 [f]	18.9 [d]	17.6 [h]	13.5 [f]	10.7 [f]	6.7 [f]
Wheat straw	7 [f]	18.5 [i]	17.2 [g]	8.5 [f]	6.0 [f]	3.4 [f]

[a] Average fresh matter basis moisture content when it is fed; [b] Dry matter basis; [c] Kirchgeßner et al. (2008); [d] Feedipedia (2012); [e] Domalski et al. (1986); [f] NRC (2001); [g] KTBL Energiepflanzen (2006); [h] average 3-7% less than HHV based on Kaltschmitt et al. (2009); [i] Derived from Stanton and LeValley (2010); [j] VEEPRO HOLLAND (2012); [k] Coppock et al. (1987); [l] Shaver (2008); [m] Pioneerfeed Company (2012); [n] Klinge (1989); [o] Schwab et al. (2003); [p] Silva et al. (2010); [q] Spiekers & Potthast (2004); [r] Newkirk (2009); [s] Bernard (2012);

2.6.2.6.3 Seed

The energy equivalent of seed depends on its production methods and conditions. There are only a few studies and limited information regarding seed production and the energy used in its production (Ortiz-Canavate & Hernanz, 1999).

The energy embodied in seed production includes the pre-harvest and postharvest energies that are consumed during its production and preparation as seed. Postharvest energy requirements of alfalfa seed production include drying, sorting, disinfecting, and packaging and reach 46% of the energy consumed during seed production on the farm (Heichel, 1980). There is not enough data on energy consumption in production available for recently improved high-yielding hybrid seeds. Table 11 summarises the energy equivalents of different seeds and tubers stated by Heichel (1980) and adopted and cited in Ortiz-Canavate & Hernanz (1999).

Table 11 Embodied energy value (EEV) in seed and tuber production (Heichel, 1980; adopted and cited in Ortiz-Canavate & Hernanz, 1999)

Crop	*EEV MJ kg^{-1}*	*Crop*	*EEV MJ kg^{-1}*
Alfalfa	230	Rice	17
Clover	135	Sugar beet	54
Corn hybrid	100	Forage hay	88
Wheat	13	Rapeseed	200
Barley	14	Sunflower	20
Oats	18	Potato	93
Soya bean	34	Cotton	44

2.6.2.6.4 Manure

Dairy cattle (with 650 kg mass, 7,000 kg yr^{-1} milk production, and 20 kg d^{-1} DM intake) produce nearly 60 kg of fresh manure per day (Safley et al., 1986). Weiss & St-Pierre (2010) found that fresh manure output is approximately 3 kg per kg of DM feedstuff intake. The fresh manure or “as-excreted manure” is a mix of faeces and urine with a ratio of 2.2/1 by mass (Safley et al., 1986). Manure is distributed on farms to improve the soil structure and utilise its nutrient content, as it is a renewable replacement for chemical fertilisers. Manure is a resource of biomass energy, and recently, it has been used in gasifiers or biogas plants to produce heat or gas fuel. As with other biomass energy resources and biomass products, there is the issue of whether the heating value of manure or allocated embodied energy in its production should be used as an energy equivalent of manure input in farms. Manure is a by-product of cattle farming, and therefore, the energy embodied in manure production should be investigated within the energy analysis of cattle farming. Canakci et al. (2005) used a value of 0.3 MJ kg^{-1} as the energy equivalent of manure, without assessing the moisture content and heating value basis of this value. Manure is normally mixed with wash water, straw or other bedding materials. Fresh manure has a water content of approximately 87.5% (Weiss & St-Pierre, 2010), but during storage in the lagoon or barnyard, its moisture can be reduced. The HHV of dry manure is approximately 14 MJ kg^{-1} manure (Beck et al., 1979). The value used by Canakci et al. (2005) is significantly less than the HHV of fresh manure (with 80% moisture, the HHV is 2.8 MJ kg^{-1} fresh manure).

Another way to define the energy equivalent of manure could be based on the amount of its nutrients, especially N, and thus, the replacement ability of manure relative to chemical fertilisers. The nutrient content of manure, as well as its heating value, depends on various factors, such as cattle category, feedstuff, and how manure is stored and for how long. The N content of manure is generally in two N compositions: inorganic and organic. Inorganic N (ammonia N) is the predominate part. Organic N is not available for use as a nutrient by crops, but every year, 30-50% will breakdown into inorganic N, which can be used by plants (Pennington et al., 2003). Cattle manure reportedly contains 5.6 kg N, 1.5 kg P (3.4 kg P_2O_5), and 3 kg K (3.6 kg K_2O) in each fresh manure tonne, according to Pimentel et al. (1983). The reported amount by Weiss & St-Pierre (2010) was 5.9 kg N and 0.77 P (1.8 kg P_2O_5) per tonne of fresh manure, while the reported amount by Pennington et al. (2003) was 5.0 kg N, 1 kg P (2.3 kg P_2O_5), and 4.2 kg K (5.0 kg K_2O). Depending on the techniques, during manure storage, 15-80% of N content could be lost, and 1-40% of N content after application on the farm could also be lost (Pennington et al., 2003). At an average daily temperature between 5-25 °C, the reported losses of total manure nitrogen during storage are between 40% and 60% (Safley et al., 1986). With an assumption of 50% of N loss (for the inorganic part) during manure storage and application on a farm, and comparing the nutritional value of manure with the embodied energy in chemical fertilisers in the form of N, P_2O_5 and K_2O (table 9), the energy value of fresh cattle manure is calculated to be 0.33 MJ kg^{-1}, which is similar to the figure used by Canakci et al. (2005).

Depending on the available opportunities in each region for the use of manure, its energy equivalent could be defined in each case, whether as its LHV or nutrients replacing availability value.

2.6.2.7 Transportation

Nearly half of the energy consumed in food industries in developed countries is due to transportation, marketing and household preparation (Hernanz & Ortiz-Canavate, 1999). In these countries, also in Iran, most food transportation systems are based on truck transportation. The energy consumed in Swedish truck transportation has been estimated to be 1.4 MJ t^{-1} km^{-1}, including both direct and indirect energy consumption in vehicles and infrastructure

(Börjesson, 1996), while Hülsbergen et al. (2001) and Rathke & Diepenbrook (2006) used a value of 6.3 MJ t^{-1} km^{-1} transport for Germany. It seems that this value is overestimated. The fuel consumption of trucks has been reduced during the last few decades. Therefore, based on the transportation fleet composition of each country as well as different amounts of consumed energy in infrastructures, the embodied energy in transportation could vary significantly. Table 12 shows the energy demand of different types of transportation used by Hernanz & Ortiz-Canavate (1999).

Table 12 Energy demand of different transportation systems (Hernanz & Ortiz-Canavate, 1999)

Transport system	*Energy equivalent MJ t^{-1} km^{-1}*
Boats	0.3 - 0.8
Railroads	0.4 - 0.9
Trucks	1.6 - 4.5
Airplanes	1 – 30

To calculate the energy input from the transportation of input materials, it should be considered that in the energy equivalent of some of input materials, such as machinery, fertiliser and pesticide, energy input from transportation is already included.

2.7 Energy outputs from a dairy farm

2.7.1 Milk energy

The energy content of milk depends on the milk components of fat, protein, and lactose. Fat and protein are measured frequently. Therefore, the energy content of milk is calculated through the following formulas:

$$HHV_{Milk}(MJ/kg) = 0.370 \times fat\ (\%) + 0.210 \times protein\ (\%) + 0.950 \qquad \text{Equation 6}$$

$$HHV_{Milk}(MJ/kg) = 0.389 \times fat\ (\%) + 0.229 \times protein\ (\%) + 0.804 \qquad \text{Equation 7}$$

Equation 6 (Kirchgeßner et al., 2008) and equation 7 (adopted from NRC, 2001) give nearly the same result for a given sample of milk.

Regarding different fat and protein contents of milk from different farms, a constant basis of energy for milk is used to compare the farms. The Gaines formula, introduced in 1928, corrects the milk yield of farms for 4% fat milk, which has 3.16 MJ kg^{-1} of energy content. The

Gaines formula to calculate the 4% fat-corrected milk (4% FCM) is as follows (adopted from NRC, 2001):

$$FCM_{4\%}(kg) = 0.4 \times milk\ yield\,(kg) + 0.15 \times fat\ (\%) \times milk\ yield\,(kg) \qquad \text{Equation 8}$$

The FCM formula has been widely used to convert the milk yield even at the 4% fat level (Kraatz, 2012) or 3.5% level (Erdman, 2001). Regarding the availability of fat and protein content of produced milk, the energy corrected milk (ECM) is calculated through equation 9 (Ulbrich et al., 2004):

$$ECM\,(kg) = \left[(0.38 \times fat\ (\%) + 0.21 \times protein\ (\%)) + 1.05\right] \times milk\ yield\,(kg) / 3.28$$

Equation 9

The resulting ECM has the same dimension as milk yield (kg) but is corrected for 4% fat and 3.4% protein, which has 12.8% DM and 3.15 MJ kg^{-1} energy content (through equation 6).

2.7.2 Meat energy

Meat quality and its energy content (HHV) are dependent on the cattle category and meat tissue in the cattle. Klinge (1989) introduced the caloric value of 8.8 MJ kg^{-1} of fresh cattle meat as an average of different types of meat. The amount of meat from an animal depends on several factors, such as the cattle breed, cattle category (dairy or beef), age and dietary program.

If the latent energy in the slaughtering residues of cattle (e.g., blood, skin, internal organs, head, and legs) is neglected, the remaining carcass consists of meat and fat as the useful parts and the bone and tendons as useless parts. The percentage of cold carcass weight to empty body mass of an animal is known as the dressing percentage. The empty body mass is 90-96% (Aass & Vangen, 1997) of the live animal mass. Table 13 summarises the results of some related studies to determine the dressing percentage and meat and fat amount of carcass mass.

Table 13 Cattle dressing percentage and meat proportion of carcass mass.

Cattle type	*Mass kg empty body*	*Dressing (cold) % of empty body*	*Meat % of carcass*	*Bone % of carcass*	*Subcutaneous Fat % of carcass*	*Reference*
Bull	555	58	70	19	11	Afolayan et al. (2002)
Bull	588	60	76	16	6	Pfuhl et al. (2007)
Calf	44	58	65	35	-	Brekke & Wellington (1969)
Calf	90	61	72	28	-	Brekke & Wellington (1969)
Calf	131	63	75	25	-	Brekke & Wellington (1969)
Bull	197	50	-	-	-	Khalafalla et al. (2011)
Bull	243	50	-	-	-	Khalafalla et al. (2011)
Bull	297	53	-	-	-	Khalafalla et al. (2011)
Bull	341	53	-	-	-	Khalafalla et al. (2011)

As shown in this table, for different types of cattle in different studies, the dressing percentage is 50% to 60% of the empty body mass, and 65 to 80% of the carcass is meat and subcutaneous fat. These studies were conducted for beef and veal Holstein breeds. Dairy cattle save more internal fat as an energy deposit (Pfuhl et al., 2007).

2.8 Allocation of embodied energy

Agricultural processes generate one or several by-products in addition to the main products. One of the issues in LCA and energy analysis is how to allocate inputs such as production energy to the product and by-product. The allocated energy to the product and by-product depends on the methodology used and can cause significant differences in the results of the energy analysis. To attribute the production energy completely to the target product is the simplest solution of allocation. In this case, the by-product is valued as free from the energy. However, this solution is not an adequate method, at least in agriculture, because it neglects the by-product that can sometimes have the same energetic value as the product. To find a solution for the allocation, the International Organisation for Standards have introduced a procedure published in the ISO standard 14041 (1998) and later revised in ISO 14044 (2006) as follow:

- Allocation should be avoided, wherever possible, by dividing the process into sub-processes and collecting data for each sub-process or through expanding the system to include the same product or function of an alternative system.

- Where allocation cannot be avoided, the allocation should reflect a physical relationship between the products or functions.
- Where such a physical relationship cannot be used, the allocation should reflect other relationships between products or functions, for example, the economic value of the products.

In the process of subdividing production, detailed data of the sub-processes should be collected, and only the necessary sub-processes attributed to each part of the product should be taken into account for its production energy. Subdivision can eliminate the allocation issue, or at least reduce it. System expansion means that the embodied energy in a by-product is assumed to be same as the embodied energy in an alternative product, which is replaced in a special purpose. This method in LCA is also called a “substitution”, “displacement”, or “replacement” allocation method (Edwards & Anex, 2009). Figure 7 illustrates these two procedures of allocation of production energy.

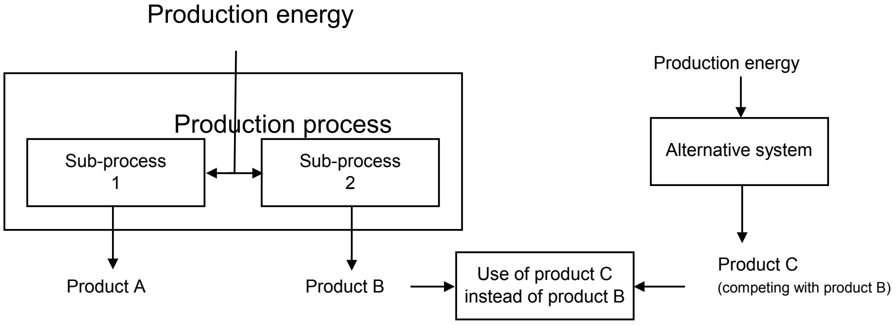


Figure 7 Illustration of the process division and system expansion procedure in allocation of production energy (adopted from Ekvall & Finnveden, 2001)

In energy analysis, allocation of the consumed energy to product and by-products is carried out by comparing them to physical properties (e.g., volume and quantity of material), energetic values (e.g., HHV, LHV and MEV) or economic prices (VDI 4600, 2012).

It is difficult or impossible to introduce a common way to allocate the embodied energy in the production process to products and by-products. Kraatz (2009) also used economic properties for allocation in an energy analysis of dairy farms. Because the price proportion of products and by-products can vary over time or between regions (particularly in countries where pricing policies can vary rapidly), the use of other properties, especially energetic values, in energy analysis seems to be more reliable, enduring and rational. In the substitution of feedstuffs with each other, feeding values and the substitution rate or the portion of replaced materials may affect the dietary characteristics of feed mix. Edwards and Anex (2009) used a feeding model to assess the effects of different substitution rates and then credit the replacer feed. However, substitution methods can also change over time and between regions. By employing new technologies or different management systems, the energy value used for a product can be different, depending on the product and by-product consumption purposes.

Cotton production is an example of complexity in allocation. The purpose of cotton production is lint. However, in the United States, 18% of a cotton producer's income is from cottonseed (Blasi & Drouillard, 2002). Lint, cottonseed and gin trash are three components of cotton that has been freshly picked with a spindler harvester. Lint is used in the textile industry, while cottonseed and gin trash are feedstuff or bio-energy resources. Cotton fuzzy (cottonseed with linter) and cottonseed meal are edible to ruminants and are rich in protein, fat, fibre, and energy. Cottonseed meal is generally a replacement for rapeseed meal and soybean meal. After harvesting and separating the lint (ginning), the seeds can be fed directly to livestock, as well as be crushed (Anonymous, 2011). While cottonseed is itself a by-product of the cotton industry, four other by-products come from cottonseed crushing: oil, meal, hull and linter. Extra energy is consumed to separate the linter (delinting) and hull (dehulling) from cottonseed to prepare it for oil extraction purpose. LCA modelling of cotton production is a complex process (Anonymous, 2011).

2.9 Energy intensity in feedstuffs and dairy farm productions

The estimated energy demand for the feedstuffs production and dairy farm productions widely varies in literature, according to existing investigations and methodologies. Table 14 provides the values for the energy intensity of feedstuffs used for dairy cattle, as found in literatures.

The energy intensity calculated by Refsgaard et al. (1998) for cereals was approximately 2.6 MJ kg^{-1} DM with a yield of 3,000-4,000 kg ha^{-1}. In a study in Iran it was found that the energy intensity for maize corn is 6.25 MJ kg^{-1} DM with FM yield of 7,000 kg ha^{-1} (Lorzadeh et al., 2012). The energy intensity calculated for rapeseed is 9.1-10.7 MJ kg^{-1} DM for a study in Iran by Mousavi-Avval et al. (2011) with yield of 1,900 kg ha^{-1} FM and much higher than for Germany (5.2) estimated by Kraatz (2009).

Table 14 Energy intensity of feedstuffs for dairy cattle.

Feedstuff	*Location*	*Energy intensity (MJ kg^{-1} DM)*	*Reference*
Alfalfa			
	Denmark	2.98	Refsgaard et al. (1998)
	Estonia	1.59	Frorip et al. (2012)
	Greece	2.53	Tsatsarelis & Koundouras (1994)
Barley			
	Estonia	3.81	Frorip et al. (2012)
	Germany	1.88 - 2.30	Kraatz (2009)
	Iran	6.58	Ghasemi Mobtaker (2010)
	Iran	13.59	Sahabi et al. (2013)
Maize corn			
	Estonia	5.13	Frorip et al. (2012)
	Iran	6.25	Lorzadeh et al. (2012)
Maize silage			
	Belgium	2.2	Meul et al. (2007)
	Estonia	2.33	Frorip et al. (2012)
	Germany	2.24 - 2.49	Kraatz (2009)
Rapeseed			
	Germany	5.15	Kraatz (2009)
	Iran	9.07 - 10.67	Mousavi-Avval et al. (2011)
Wheat			
	Estonia	2.33	Frorip et al. (2012)
	Germany	1.85	Kraatz (2009)
	Iran	6.26 - 8.41	Shahin et al. (2008)

Table 15 shows the energy intensity in milk production as calculated by some investigations for dairy farms with different milk yields in cows from European countries. The energy intensities are based on the cumulative energy demand in dairy farming, but some exceptions are seen e.g. the energy input from electricity was calculated other than primary energy basis by Frorip et al. (2012). However, the methodologies used in the estimation of the energy intensity differed slightly. Bockisch and Ahlgrimm (2000) neglected the energy demand for when heifers replaced cows. Grönroos et al. (2006) and Refsgaard et al. (1998) also neglected heifer rearing for cow replacement. The allocation of the input energy to by-product feedstuffs is another source of variability in the investigations. Abel (1997) used economic relationships between dairy products; accordingly, he allocated 70-75% of the total energy input to milk, 22% to meat and 3-8% to excrement. Refsgaard et al. converted meat yield to milk yield by energetic relationships which resulted in 96.5% allocation to milk and 3.5% to meat. Grönroos et al. (2006) allocated rapeseed production energy to oil and meal according to their mass yield. He allocated 87% of the total energy input of milk production to milk and 13% to meat, as done by Cederberg & Stadig (2003), in a way that was dependent on boundary expansion method (Substitution). Grönroos et al. (2006) did not allocate any energy input to excrement. One of the arguments of Cederberg & Stadig (2003) to system expansion was the high replacement rate (37% or 72 kg boneless meat yield per cow and year) in dairy farms in Sweden. Kraatz (2009) included the energy demand for rearing heifers in the energy input of milk production. Furthermore, she discussed various possibilities on how to allocate the whole energy input to milk, meat, calf, and excrement production by using biological and physical relations. The energy input for milk, meat and calves was allocated according to the energy demand of cattle for maintenance and lactation. The energy allocated for excrement was performed according to the substitution of manure with chemical fertilisers. She carried out these allocations under several variants and provided a discussion. The reason not to including the energy output from excrement in the allocations is the grazing of the cows direct on the farm which causes to neglect the excrement in both input and output sides by Refsgaard et al. (1998), Grönroos et al. (2006) and Thomassen et al. (2008). Beside the energy input sources considered in the investigations, allocation method, and also the milk yield and milk type should be considered for the comparison of different reports.

High share of energy input from feedstuffs makes the energy intensity of feedstuffs as the main determinative factor in the energy intensity of milk. Refsgaard et al. (1998) found that 70% of the energy input in milk production is from feedstuffs, 20% from direct energies and 10% from facilities (e.g. building and machinery) in stalls for conventional milk production. 73% of energy intensity in conventional milk was from feedstuff by investigation of Grönroos et al. (2006). Thomassen et al. (2008) found the share of the indirect energies (feedstuffs, building and machinery) to be 90% and of direct energy 10%. In the investigation of Kraatz (2009), 50% of energy input was from feedstuffs, 27% from, direct energies, and technical facilities, 20% from heifer rearing and 3% from building. Therefore, the feeding plan and grazing possibility make considerable differences in the results. In two systems of dairy farming compared by Kraatz (2009), the lower energy intensity in pasture (0.5 MJ kg^{-1} DM), leads to lower energy intensity in milk produced in the dairy farms with even half day grazing plan. She found the energy intensity of milk in dairy farms with half day grazing plan to be 3.54 and without gazing plan 4.3 MJ kg^{-1}.

Table 15 Energy intensity in milk production according to different studies.

Study location	*Milk type*	*Milk yield ($kg\ cow^{-1}\ yr^{-1}$)*	*Energy intensity ($MJ\ kg^{-1}$)*	*Reference*
Germany	-	7,000	4.8	Abel (1997)
Denmark	ECM Conventional	7,300	3.3 - 3.6	Refsgaard et al. (1998)
Denmark	ECM Organic	6950	2.2 - 2.9	Refsgaard et al. (1998)
Germany	-	7,000	4.7	Römer et al. (1999)
Germany	-	6,600	3.0	Berg and Scholz (2000)
Germany	ECM	6,182	2.7	Bockisch and Ahlgrimm (2000)
Finland	1.5% fat Conventional	7,700	6.4	Grönroos et al.(2006)
Finland	1.5% fat Organic	6,800	4.4	Grönroos et al. (2006)
Belgium	Fresh	5,521	4.4	Meul et al. (2007)
Netherland	4.4% fat Conventional	7,991	5.0	Thomassen et al. (2008)
Netherland	4.5% fat Organic	6,138	3.1	Thomassen et al. (2008)
Germany	ECM	8,000	3.5	Kraatz (2009) and Kraatz (2012)
Finland	-	-	3.0	Mikkola and Ahokas (2008)
Estonia	Fresh	-	5.3	Frorip et al. (2012)

The energy intensity of beef meat production in Germany for conventional keeping systems was 56.35 MJ kg^{-1} and 25.50 MJ kg^{-1} for organic systems according to the data from GEMIS 3.1 (Taylor, 2000). In the UK, the energy intensity of cattle meat production was estimated to be 28 MJ kg^{-1} of the carcass mass, in which the energy intensity per kg of fresh milk was 2.5 MJ kg^{-1} (Williams et al., 2006). Frorip et al. (2012), calculated the energy intensity for meat as 69 MJ kg^{-1} for Estonia using 6.5 to 9.22 MJ kg^{-1} caloric value (HHV) for whole empty body mass. They also calculated the energy input in meat and milk by HHV basis scenario and found it to be 255 MJ HHV kg^{-1} meat and 20 MJ HHV kg^{-1} of milk.

3 Methodology

3.1 Study framework

The transparency of the study methodology is an important aspect of the energy analysis that makes the results of one study comparable with the results of other studies. Therefore, standard guidelines were used in this study to attempt to clearly describe the methodologies in question.

The main framework of this study is based on the spirit of the methodology introduced in 1974 by the International Federation of Institutes for Advanced Studies (IFIAS) for energy analysis (IFIAS, 1974). However, the new and more detailed guidelines for cumulative energy demand (CED) and life cycle assessment (LCA) concepts introduced respectively by the Association of German Engineers (VDI 4600, 1997, revised in 2012) and International Standard Organisation (ISO 14040 and 14044, 2006) were used.

As described in section 2.3, the IFIAS methodology consists mainly of the following steps: establishing the boundaries of the understudied system, identifying the underlying factors, assigning an energy equivalent to each factor, multiplying the actual quantity of each factor by its energy equivalent, identifying and quantifying the output product(s) and establishing the energy allocation criteria of the products and by-products, and finally comparing and relating the product or its energy equivalent to the energy consumed within the production system (IFIAS, 1974). To properly establish the boundaries of the understudied system and identify the underlying factors, the VDI 4600 guideline, which was specialised for energy analysis, was selected. However, ISO 14040 and ISO 14044 standards have also been introduced for environmental assessment, but they were used to establish the methodological structure for this study.

In reference to ISO 14040, a comprehensive LCA study has several stages (ISO 14040, 2006), which are as follows:

a) The goal and scope definition phase, which is used to determine the goal, scope, system boundary, level of detail and depth and breadth depending on the aims of the study.

b) The life cycle inventory analysis phase (LCI), which includes an inventory of input-output data with regards to the system under study and the goals.

c) The life cycle impact assessment phase (LCIA), for providing additional information to help assess a system.

d) The interpretation phase, which is the discussion stage for addressing the results of the inventory analysis phase or the impact assessment phase.

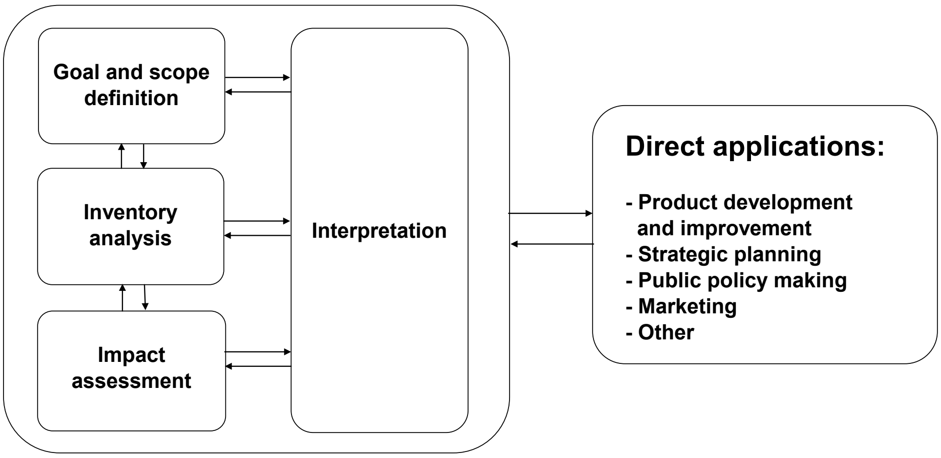


Figure 8 Stages of an LCA study (from: ISO 14040, 2006)

According to this concept, the impact assessment phase could be neglected. Without the LCIA phase, the input and output data in the inventory analysis phase could be interpreted and applied directly to achieve these goals. Figure 8 graphically demonstrates these phases and their connection order. The following methodology for this study is expressed with the intent of maintaining the LCA methodology format.

3.2 Study goals

To achieve more energy-efficient and sustainable dairy cattle farming, the goals of this study were defined as the investigation and evaluation of dairy cattle farming in Iran by estimating energy efficiency indicators. This study includes an investigation of the energy efficiency of feedstuff production and various cattle farms that differ in terms of herd size, breed purity, milk yield, region and management systems. The investigation focused on the calculation of energy indicators and the energy intensity used in the production of feedstuffs with milk and meat as the main indicators and gives suggestions for possible solutions for farmers or agricultural policy makers to improve and develop better energy efficiency in dairy cattle farming.

3.3 Study scope

3.3.1 Production system

The system under investigation was dairy cattle farming and the production of milk and meat (or cows). For this study, the dairy system consisted of two individual units: the feedstuff production unit and the dairy cattle farm unit. Feedstuff production consisted of output from the first unit and input or feedstock for the second unit. These products are termed intermediate products or flows (ISO 14040, 2006). In this study, the main and most important unit was the dairy farm unit. Therefore, different dairy farm systems were compared under the assumption that they employ the same feedstuff production methods.

3.3.2 System boundaries

In this study, the boundaries of the dairy farming system started with the feedstuff production in feedstuff farms and ending with the production of milk, meat and manure at the output gate. Therefore, the system boundaries included the consumption of the primary energy and material resources in the production of energy carriers, materials and facilities used or consumed in feedstuff farms, dairy farms and required transportation. In the studied regions, the feedstuff farms and dairy cattle farms were completely separated, and the dairy farms largely had no grazing facilities. The resulting excrement from the dairy farms was sold to the crop production farms. The system was divided in two separate sub-systems: "feedstuff farm unit" and "dairy farm unit". Thus, these two sub-systems were investigated separately, which made it possible to evaluate each unit individually and ultimately combine the results in accordance to the estimated energy efficiency indicators.

The sub-system of the feedstuff farm unit began with the extraction of raw materials and energy resources and was confined to the output gate of feedstuff farms. The dairy farm sub-system started from the output gate of the feedstuff farm and was confined to the output gate of dairy farms. For inputs other than feedstuffs, the sub-system of the second unit began with the extraction of energy and material resources and continued until the farm output gate. Figure 9 shows the dairy farming system with energy and material flowing through it.

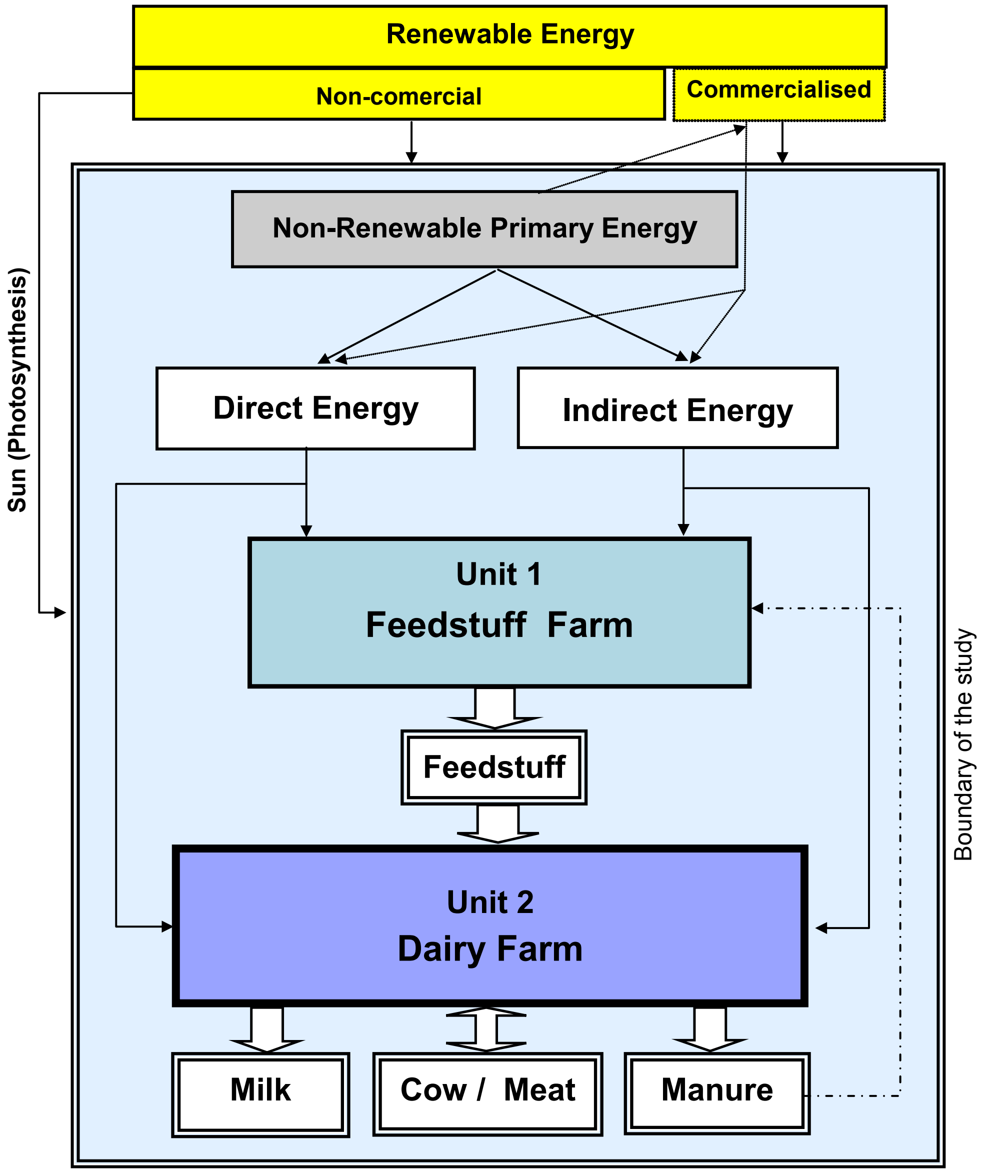


Figure 9 Energy input / output system in dairy cattle farming.

The non-commercial energy types, e.g., the solar, wind, soil and water energy entering the system, were excluded from the system boundaries and not calculated as energy inputs. The primary energy or raw material resources inside the system boundary were in the form of direct energy as energy carriers or indirect energy as materials and facilities. Physical non-renewable energy from the fabrication and production of renewable energy resources were included within the boundaries (for example, non-renewable energies used in the fabrication of wind or solar energy facilities and non-renewable energy used in seed production).

According to the scenarios explained in section 2.6.2.6.1, calculating the energy equivalent used for feedstuffs (the output of unit 1 and input of unit 2) in combining the two sub-systems and calculating the energy efficiency indicators were accomplished in two ways. In the first scenario, the feedstuff energy equivalent was designated as the energy embodied in their production. In this study, this scenario is called the EEV scenario. In the second scenario, the energy equivalent of the feedstuff was given a higher heating value. This scenario is called the HHV scenario in this study.

The second scenario includes the commercial renewable energy stored in feedstuff (from photosynthesis) within the boundary of the study, in contrast to the methodology explained before and used in scenario one. However, this difference was introduced to compare the caloric values in feedstuff and dairy products.

3.3.3 Farm selection and data acquisition

As a result of different climates, cultures and geographic specifications, there is a wide range of diverse cattle keeping systems within Iran. In this study, the cattle farming system in north-western Iran was selected, including the provinces of West Azarbaijan, East Azarbaijan, Ardabil, and Zanjan. According to the dairy specification in Iran (figure 2, p. 10), cattle keeping systems in north-western Iran are in the middle of a spectrum of prevalent systems from central, north, and south Iran. The systems are distinguished by herd size, milk yield per cow, feeding materials, and management of the different dairy farms. In the following text, the selection criteria of farms for both feedstuff and dairy farms as well as the data acquisition methodology are revealed

3.3.4 Feedstuff farm selection

Alfalfa, maize silage, maize corn, barley and oilseed meal are the feedstuffs for Iranian cattle farming. In the Azarbaijan provinces (West Azarbaijan, East Azarbaijan and Ardabil), the main regions for alfalfa production are Moghan plain, Miandoab, and Naghade. Maize silage and corn are produced in the Moghan plain (Ardabil province) and the Kermanshah and Khuzestan provinces. Barley is mainly imported from Ukraine and Canada, but it is produced inside the country in a few regions as well as the Moghan plain. Cotton and sunflower cake are mainly imported from central Asia. Soya and rapeseed cake are produced in the Kermanshah and Gorgan provinces.

The energy efficiency of these feedstuffs should theoretically be investigated within their original production regions. Therefore, in the absence of any similar or related studies involving energy efficiency, the production input and output data should be collected from the farms that produce at least the majority of feedstuffs used in the selected cattle farms. In this study, the region that produces most of these feedstuffs was chosen. Therefore, the Moghan agro-industrial company in the Moghan plain was chosen for investigating the energy efficiency of feedstuff production.

There is a large area under cultivation by the Moghan agro-industrial company, which produces diverse products with mechanised farming systems. The 40-year-old company has experience in applying new technologies related to mechanised farming, and it has introduced new or unconventional products to the region, making it a pioneer in the field. The company was established by the government in 1971 with more than 63,000 hectares of uncultivated Moghan plain land (Anonymous, 2013). It has since become one of the largest agricultural companies in Iran. This company produces a wide range of agricultural and horticultural products, which are sold directly to the markets and processed in their own food firms inside the company or are consumed as feedstuff in the cattle farm unit, which has recently grown to almost 15,000 cattle.

Following the patterns used by the Moghan Company and adopted by other private companies and farmers in Moghan, which have relatively larger farm sizes in comparison to farms in other regions, these methods have led this plain to become a major supplier of agricultural products.

The Moghan plain is located in north-western Iran and west of the Caspian Sea, between a latitude of 39° N and 40° N and a longitude of 42° E and 48° E, with an average altitude of 45 m over sea level (Anonymous, 2013). The annual rainfall is 265 mm, the average minimum temperature is 9.7°C, the average maximum temperature is 20.5°C, and the average annual temperature is 15.1°C (Tavousi & Delara, 2011). As a result of the high soil fertility, the high average temperature and available water resources from dams and irrigation networks from the Aras river, this plain contributes a high share of food production and feed delivery to dairy cattle farms in neighbouring provinces.

3.3.4.1 Feedstuff data acquisition

The necessary production input and output data were collected by making field observations and measurements or technical calculations from the Moghan Company farms. The study feedstuffs from the Moghan Company were alfalfa (1,200 ha), barley (2,000 ha), maize corn (3,000 ha), maize silage (1,000 ha spring maize silage and 2,000 ha summer maize silage), rapeseed (3,000 ha) and wheat (7,000 ha). Selected products or by-products were used directly or indirectly as cattle feedstuff. The farms were segmented into several ten-hectare farms and cultivated in yearly crop rotation. Propitious agricultural conditions and water availability during the long farming season make it possible to cultivate as many as two crops each year. The cultivation of maize forage as a secondary product following the harvest of cereals or oilseeds as a primary product is very common. With nearly the same water delivery and climate conditions during different years as well as stable operational procedures, no significant differences were observed in the production input and output data for the company. Therefore, the average value for 3 years, ending in the year 2010 (the year 1389 in the Iranian calendar), was calculated.

Energy efficiency indicators for feedstuffs (e.g., cottonseed and soya bean) not investigated here were derived from the scientific literature using studies with similar regional conditions.

All cultivation machinery operations and materials applied and consumed during production were included in the data acquisition. These data consisted of the production yield, consumed material (seed, manure, fertiliser, pesticide and water), fuel consumption, duration and repetition of machinery operations, and type and weight of machinery. Machinery operations such as sub-soiling or manure spreading are repeated every 5 years and were distributed equally over 5 years, although their effect is not the same for the years covered in this study.

3.3.4.2 Dairy farms selection

Dairy farms were selected in view of the differences in dairy cattle numbers per farm, milk yield, region, and year. The number of dairy cattle in the selected farms should reflect the herd size distribution in Iran as described in section 2.1 (85% of dairy cattle are kept in herds with less than 51 heads, 5% in herds between 51 and 100 heads and 10% in herds with more than 100 heads). The dairy farms were selected from three provinces (West and East Azarbaijan and Zanjan), which are representative of prevailing dairy farming methods in north-western Iran. These provinces were selected according to the dairy distribution in 5 regions. Cattle in these regions are cross breeds of Holstein and a local breed, with different degrees of breed purity. Data were gathered for 2008, 2009 and 2010.

On the one hand, there was an intention to gather data from a high number of farms to enable representative results with a high degree of accuracy. On the other hand, the required data could not be obtained from some of the selected dairies. These dairies were especially large farms with several hundred cattle. Therefore, only two dairies with more than 100 heads of dairy cattle could provide the requested information. Lastly, the required data were obtained from 24 dairies in 4 regions. Fifteen dairies were in East Azarbaijan (3 in region 1 and 12 in region 2), 8 dairies were in West Azarbaijan (region 3), and only one dairy was located in Zanjan (region 4).

3.3.4.3 Dairy farm data acquisition

The desired data were obtained from the dairies by using a questionnaire designed for this purpose. The questions were arranged in 5 groups. The first group was about the number and mass of different cattle categories (calves, bulls, heifers and cows) at the beginning and end of each year and the number of cattle sold or bought in that year along with the selling time. The second group included questions about the amounts and types of annual feedstuff consumption for the dairy and the daily feed intake of the cattle categories. The building area specifications for materials and roofed and non-roofed areas and the specifications for machinery used in the dairies, i.e., their nominal power, mass and usage hours, made up the third group of questions. Direct energy resource consumption was obtained by the forth questions group. The last questions were about the annual milk production of the dairy farms, the amount of manure produced, the average daily milk yield, dairy cattle replacement rate, calving interval, etc. Due to the lack of regular measurements for some data, such as cattle body mass and the amount of feedstuffs remaining in the dairies from year to year, farmer estimations were used.

3.3.5 Functional unit

One element of the LCA study is the necessity of clearly defining the functions (performance characteristics) of the studied system. The functional unit of a system is a reference with which to normalise and quantify related input and output data and make the different systems comparable with one another in the same way (ISO 14040, 2006). In this study, the functional unit is the actual energy, which is the sum of the energy consumed to produce an asset (the section 2.5), which can be an output material as well as an input material, facility, or service. Therefore, all production information was converted to the energy value per unit of each input or output. Finally, the energy embodied in the energy-corrected milk (unit: MJ kg^{-1} ECM) was used as a functional unit to reveal the performance of a system.

3.3.6 Assigning the energy equivalents

3.3.6.1 Energy input

As described in section 2.6 (energy input equivalents), a wide range of assumptions for energy equivalents has been made in energy studies. Different assumptions for energy equivalents make it difficult to compare the results of different studies. Energy equivalents intended to quantify the inputs or outputs should be determined to clarify the study. To conclude section 2.6, the energy equivalents used in this study are used as follow:

- Equivalents of direct energies were used as listed in table 3 (p. 22), except for electricity energy which 8.4 MJ kWh^{-1} (energy of production) is used.
- Human work was not viewed as an energy input.
- Machine equivalents were calculated using the method of Bowers (1992), as shown in table 6 (p. 29).
- The building equivalent was the same as in table 8 and for the silos and open area calculated according to their dimensions and information in table 7 (p. 30).
- Fertiliser equivalents are shown in table 9 (p. 32).
- Insecticide, herbicide and fungicide equivalents were assumed to be, on average, 237, 288 and 196 MJ kg^{-1}, respectively, for the active ingredients (Rathke & Diepenbrook, 2006). The active substance amounts are in annex 4.
- The water consumption equivalent in channels and network irrigation systems was assumed to be 0.63 MJ m^{-3} water (Ozkan et al., 2004b).
- The transportation equivalent was calculated from the fuel consumption of trucks used between the farms. In the case of absent data, it was assumed to be 1.6 MJ t^{-1} km^{-1} of truck transportation (Hernanz & Ortiz-Canavate, 1999).
- Seed equivalents were used from table 11 (p. 37).
- Biomass equivalents following the EEV investigation scenario were given as the production energy presented in table 20 (p. 73) and table 21 (p. 73) and according to the HHV investigation scenario in table 10 (p. 36).

3.3.6.2 Energy output

According to the available fat and protein content data for the milk produced in the dairy farms in this study, the milk yield of the farms was converted to the energy-corrected milk (ECM) value by using equation 9 (p. 40). An energy content of 3.15 MJ kg^{-1} ECM was used as the energy output from milk production.

The energy output from live cattle, which was leaving the system to be slaughtered, was calculated according to the energy equivalent (HHV based) of its meat content. In this study, no meat quality considerations between the different cattle categories were considered. According to section 2.7.2, an average of 55% was assumed as the dressing percentage and 75% of the carcass weight makes up the meat and fat proportion. Therefore, 40% of the live body mass was used as the meat yield for any given type of cattle. Referring to Klinge (1989), 8.8 MJ kg^{-1} of cattle meat was used as the caloric value and energy output equivalent of meat.

The energy output of manure was given a value of 0.33 MJ kg^{-1} fresh matter after a literature analysis and a calculation described in section 2.6.2.6.4.

3.3.7 Allocations in this study

3.3.7.1 Allocated energy for feedstuffs

The feedstuff energy content can be quantified depending on the animal species to which it is fed. For dairy cattle, the NEL indicates the energy available in feedstuff for milk production and body maintenance. The MEV can be used for all ruminants. Therefore, the MEV is used to compare or to sum the energy content of feedstuffs for different animal categories, such as calves, heifers, bulls and cows. Energy input in feedstuff production can be allocated to different parameters, thereby giving the energy content of the feedstuffs (e.g., MEV or NEL).

Furthermore, energy allocation is needed if a feedstuff is not the only product of a process, i.e., if a feedstuff is one of several products and/or by-products.

In this study, three cases were used in the allocation of production energy to different feedstuff products in dairy farms and described in the following.

Case A) Products and by-products are both used as feedstuffs:

When both the products and by-products are or can be used as feedstuffs, the production energy is allocated with the relationship of their feeding values (MEV or NEL). The energy in product A (EEV_A) is found by multiplying the actual energy in the total products (EEV_T) by the ratio of metabolisable energy of product A (MEV_A) to the metabolisable energy of total products (MEV_T), as shown in equation **10**.

$$EEV_A = \frac{MEV_A}{MEV_T} \times EEV_T \qquad \text{Equation 10}$$

This method was used for the allocation of production energy to sugar beets by products, straw and grain in cereals, and also the bran of wheat grain, which are all used as feedstuffs. This case was also used for soya beans and sunflower meal, and the metabolisable energy value of whole sunflower seed and rapeseed is reported.

Case B) The product is used as foodstuff and the by-product is used as feedstuff:

In some processes, the main aim is the production of foodstuff, and by-products can be used as feedstuff. Rapeseed meal, tomato pomace, poultry offal, meat and bone meal, and fat are by-product feedstuffs from main products which are foodstuff. In this case, when there is no information about the MEV of the main product, the HHV of the main product and by-product are used for allocation.

$$EEV_A = \frac{HHV_A}{HHV_T} \times EEV_T \qquad \text{Equation 11}$$

Extra necessary energy consumed in the preparation of by-product as feedstuff (e.g., milling of meat and bone) is included in the energy demand of by-product.

Case C) Product is used as material and by-product is used as feedstuff:

In the case that the main product is used for purposes other than bio-energy, food, or feedstuff (such as the cotton lint used in the textile industry), but by-products are used as feedstuff, the substitution method was used to credit the by-product according to the amount of displaced feedstuff. In this study, the simple substitution method was used, by crediting the replacer according to the ratio of the MEV of the replacer (MEV_A) to the MEV of replaced feedstuff (MEV_B).

$$EEV_A = \frac{MEV_A}{MEV_B} \times EEV_B \qquad \text{Equation 12}$$

In the case of products such as sugar beets and oilseeds, there is an extra consumed energy in the sugar or oil extraction processes. This energy was assigned to the energy demand of sugar or oil and not to the energy demand of molasses, pulps, and meals, which were considered by-products. This argument shows that the extra energy is not necessary for the feedstuff and has no influence on the feeding specification of the feedstuff. In other words, prior to the consumption of this extra energy, the main product could be fed to the cattle, and the extraction energy belongs to the food production.

The EEV allocation of cotton example:

When allocating the consumed energy from cotton production, cases C and B were combined. Considering that cotton fuzz can be fed to ruminants without being crushed, all the extra energy requirements are from ginning, de-linting, de-hulling and oil extraction and are excluded from the energy required for the feedstuff.

As reported in the petition of the National Cottonseed Products Association (Anonymous, 2011), the average energy embodied in cotton production with mechanised cultivation in Asia is 13.0 MJ kg^{-1} whole cottonseed and lint. During recent years, the lint to seed ratio in improved cultivars has been 1.43 (i.e., lint is 59% of the mass of fresh-picked cotton.) (Anonymous, 2011). Cottonseed consists of 16% oil, 45% meal and 39% hull, linter and waste (Blasi & Drouillard, 2002). The feeding characteristics of whole cottonseeds are very similar to soya beans, and both have a similar proportion of oil. In addition, their meals also seem to be similar in terms of feeding value, especially for MEV (table 10, p. 36). In this study, the allocation of energy, cottonseed and cottonseed meal are used as replacements for soya bean meal. In reference to the energy values presented in table 10 and also considering the 9.17 MJ kg^{-1} soya bean energy reported by Mandal et al. (2002), the allocation of embodied energy in cotton by-products was performed as detailed below:

The allocated cottonseed EEV was calculated by substituting it with the soya bean values and comparing their MEVs using equation 13 (case C).

$$EEV_{Cottenseed}\ (MJ\,kg^{-1}) = \frac{MEV_{Cottenseed}}{MEV_{Soya\ bean}} \times EEV_{Soya\ bean}\ (MJ\,kg^{-1}) \qquad \text{Equation 13}$$

$$= (16 /15.3) * 9.17 = 9.59 \text{ MJ kg}^{-1}$$

Allocated EEV in cottonseed meal was calculated by comparing its MEV with the MEV of cottonseed (case A) and calculating the allocated EEV (9.59 MJ kg^{-1}) with the following:

$$EEV_{Cottenseed\ meal}\ (MJ\,kg^{-1}) = \frac{MEV_{Cottenseed\ meal}}{MEV_{Cottonseed}} \times EEV_{Cottonseed}\ (MJ\,kg^{-1}) \qquad \text{Equation 14}$$

$$= (13 /16) * 9.59 = 7.79 \text{ MJ kg}^{-1}$$

In the same way, the cottonseed hull MEV was compared with the MEV of cottonseed (case A); the energy allocated to cottonseed hulls was found as follows:

$$EEV_{Cottenseed\ hull}\ (MJ\,kg^{-1}) = \frac{MEV_{Cottenseed\ hull}}{MEV_{Cottonseed}} \times EEV_{Cottonseed}\ (MJ\,kg^{-1}) \qquad \text{Equation 15}$$

$$= (7.3 /16) * 9.59 = 4.38 \text{ MJ kg}^{-1}$$

Allocation by substituting soya bean meal with cottonseed meal (instead of soya bean with cottonseed) and then allocating embodied energy to cottonseed and other cottonseed by-products produces the same results because this method is simply the reverse of the above calculations.

Considering the allocation methods for the products and by-products consumed as feedstuffs by the study farms (listed in table 10), the embodied energy is allocated as follows:

- Alfalfa, maize corn, maize silage, and grass silage cultivation have no useful by-product. Therefore, all the production energy was allocated to the main product.

- Barley, wheat, soya bean, tomato, and sugar beet cultivation have by-products. Thus, the production energy was allocated to grain, straw and bran in wheat and barley, pulp and molasses in sugar beet, and as well oil and meal in oilseeds, according to the ration of their MEV to the total MEV of the products and by-products (case A).
- Assuming the substitution of soya bean meal (as the main oilseed meal consumed in the investigated farms) with cottonseed, rapeseed and sunflower meal, the embodied energy in the replacement was calculated by multiplying the EEV of soya bean meal with the ratio of the MEV of the replacement to the MEV of soya bean meal (correspondent to “case A”).

3.3.7.2 Allocated energy for dairy products

The energy allocated to excrement was 0.33 MJ kg^{-1} of fresh manure as discussed in section 2.6.2.6.4.

The energy output from manure was subtracted from the energy input in a cow. Thereafter, the remained energy input was allocated to the milk and meat produced by the cow. The energy input allocation between the milk and meat was carried out according to the caloric value (MJ kg^{-1}) produced by the milk and meat yield (kg cow^{-1}) of a cow.

$$EEV_{Milk}\ (MJ\ kg^{-1}) = \frac{HHV_{Milk} \times Milk\ \ yield}{(HHV_{Milk} \times\ Milk\ \ yield) + (HHV_{Meat} \times\ Meat\ \ yield)} \times\ Energy\, input\,(MJ\ cow^{-1})$$

Equation 16

3.4 Feedstuff data processing

The collected input and output data for feedstuff crops (unit 1; figure 9, p. 50) from Moghan Company were converted to the energy input and output data for the dairy farm (unit 2) by multiplying the consumed or otherwise used amounts by their assigned energy equivalent. The output energy of feedstuff production was calculated based on HHV, MEV and NEL to find the energy equivalent.

The energy input from spreading manure was distributed equally over 5 years. Additionally, the distribution was done in perennial alfalfa and cultivated over a 5-year period for operations such as ploughing, disking, planting etc.

The energy input for transporting manure an average distance of 10 km was considerable. Therefore, this input was calculated and incorporated into the energy input from the manure spreading operation. In addition, the energy consumed in the transportation of products from the fields to the storage inside the feed-producing farm (as the output gate of unit 1) was calculated by assuming a distance of 10 km, and 35 and 55 litres of fuel consumption were used for trucks and trailers, respectively.

To calculate the EI and EP indicators for grain and straw, the energy input from the common operations between grain and straw (e.g., ploughing, fertilisation, combine harvesting, etc.) was allocated between them. The energy inputs related only to straw (bailing and transportation) or grain (transportation of grain) were added to the allocated energy inputs for straw or grain.

3.5 Dairy data processing

The data from the dairy farms for feedstuff and direct energy consumption indicated the yearly farm consumption, according to the purchase bills. This consumption and usage of machinery and building area were used without distinguishing between cattle categories. The number and average mass of different types of cattle at the beginning and at the end of each year, and also those for sold cattle, were declared by the farmers. However, the sale dates for the sold cattle or calves, the replacement dates for old cows with heifers, and the birth dates for the calves were not determined. Given that information, the following data processing was performed:

Feedstuff

The feedstuff consumption data were checked by calculating the cattle demand for feed energy intake on the basis of animal nutrition knowledge. The standard cattle energy intake requirements, as reported by Kirchgeßner et al. (2008), and the data on cattle live mass (LM), growing rates and milk yield from the investigated farms were obtained from these calculations. The energy demand for the maintenance (ED_M) of dairy cattle was calculated from the live body mass by using equation 17 (Kirchgeßner et al., 2008). To calculate the lactation energy requirement (MJ NEL), a value of 3.15 MJ kg^{-1} ECM was used, which is equal to the HHV of the resulting ECM. The total dairy cattle energy requirement was calculated by adding the energy requirement for maintenance and for lactation. Kirchgeßner et al. (2008) used a value of 1.66 to convert the NEL to the ME (q value). The NEL and ME of all feedstuffs consumed at each farm for each year were calculated by using the energy values shown in table 10 (p. 36).

$$ED_M\ (MJ\ ME\ day^{-1}) = 0.488 \times LM^{0.75}\ (kg) \qquad \text{Equation 17}$$

For the other cattle categories, the cattle growing period was divided into different categories. The live mass, average daily mass gain and average metabolisable energy requirement in each category are summarised in table 16 according to Kirchgeßner et al. (2008).

Table 16 Average daily mass gain and metabolisable energy intake for different types of cattle at different ages and live masses.

Live mass (LM) *(kg)*	*Age* *(month)*	*Mass gain* [a] *(g/day)*	*ME intake* [b] *MJ/day*
	Calves born at 38 kg (male or female)		
38-150	0-5	730	29.4
	Heifers		
150-400	5-15	830	56.7
400-550	15-25	500	75.2
	Bulls		
150-400	5-13	1000	66.9
400<	13<	1000	102.5

[a] According to Kirchgeßner et al. (2008).

[b] Average value for cattle data in this category by Kirchgeßner et al. (2008).

The number of days that cattle from each category stayed on the farms was calculated using the mass gain values given in table 16 and the farm data on the live mass of each type of cattle at the beginning / end of each year and also those sold or bought from each farm. A prediction model was established to allocate the growing period of the existing cattle to the categories listed in table 16. Then, the standard ME requirements were calculated for each cattle category.

These calculated standard ME requirements were compared with the farm data of the ME consumption of each farm for each year. This comparison helped to rectify the feedstuff consumption data by again contacting the farmers for an iterative approach, as advised by LCA analysis (ISO 14040, 2006).

Based on the calculated ME requirements for each cattle category and the derived feedstuff rations, the embodied energy in the consumed feedstuff were allocated to the cattle categories for each farm and year of investigation.

Concentrated feed

The farms were designated according to whether they were preparing concentrated feed inside the farm or buying it from other companies. Some of the farms had no mixing machines and were buying the feedstuffs and having them mixed by their neighbours. For the direct buying case, the energy embodied in concentrated feed was calculated according to the mixture of the single feedstuffs indicated by the ration receipts and the data from the other farms, which were mixing the concentrated feed by themselves. The extra energy input from machinery and electrical consumption was added according to the average mass and usage hours of the mixing machinery, the average mixing capacity (1 t h^{-1}), and the nominal motor power, assuming 50% use of nominal power.

Energy embodied in dairy facilities

In the absence of an exact separation between the cattle categories in the barns and the use of machinery and consumed direct energy, the energy embodied in the facilities was calculated and allocated to each category in several ways.

The energy embodied in the buildings, silos and open areas (concrete and fences) was allocated to each cattle category according to the days for each category in the farm and the required area inside the barns for cattle in each category. Using a scoring system in which the area requirement was 1 for a calf, 2 for heifers and bulls, and 4 for dairy cattle, this system indicates that dairy cattle need 4 times more land than a calf.

The embodied energy in milking machines and milk coolants were allocated only to the dairy cattle. For the other machines, e.g., feed mixers, tractors, and water pumps, the embodied energy was allocated with the same ratios used in the allocation of the energy embodied in the feedstuffs.

The electricity consumed by milking machines and milk coolants was allocated only to dairy cattle. This consumption was estimated by recording the nominal power of their motors and their hours of use and by assuming 50% use of nominal power. The electricity consumed by mixers and water pumps was allocated according to the allocated feedstuff in each category. The electricity, diesel or gas consumption consumed for lighting, households and tractors (for excrement gathering and feedstuff displacement) was allocated according to the ratios used in building energy allocations.

Energy embodied in live cattle

The energy embodied in live cattle was the sum of the allocated energies to each cattle category from different energy input resources. The average number of cattle from each category on the farms was determined according to the mass gain of cattle and estimations made by model predictions. The first cattle category was that in which the calves weighed less than 150 kg. Each calf was an energy input for a heifer with less than 400 kg of body mass, besides the other inputs. In addition, a heifer with less than 400 kg of mass was an energy input for a heifer of up to 550 kg. A heifer was also an energy input for a cow. The energy from the manure of each cow was subtracted from the total energy input.

For the bull cattle, an individual with less than 400 kg body mass and a bull over 400 kg was used to calculate the energy input in cattle. The newborn calves were not considered in the energy analysis.

3.6 Statistical analysis model

Statistical analyses for the dairy data were carried out with SAS 9.3 software. The mixed procedure (PROC MIXED) in SAS fits a variety of mixed linear models to data, and it was used to make statistical inferences and test the possible effects of different factors influencing the energy input in dairy products.

Dairy data were gathered during 2008, 2009 and 2010 from 24 dairy farms in 4 regions. The feeding pattern, cattle milk yield, mechanisation status and herd size were different for each location. Therefore, a mixed linear model was created and tested to find the significant influences on the milk production energy input by using a significance level of $\alpha = 0.05$.

$$EE_{ijk} = \mu + R_i + Y_j + RY_{ij} + pM + nC + f_k + e_{ijk} \qquad \text{Equation 18}$$

In which EE_{ijk} is the embodied energy in the output product (e.g., milk or meat), μ determines the general mean of embodied energy, R_i and Y_j represent the fixed effects on the region and year and RY_{ij} represents their interactions. p is the regression coefficient for M the milk yield of cattle ($kg\ yr^{-1}$ cow^{-1} ECM). n is the regression coefficient and C cattle number in the herd. The f_k term represents the covariable estimates for farms, and e_{ijk} expresses the random residues. In comparison to this original model, the model was reduced by removing its insignificant parts or was changed to test the more interactive effects between the parts in some cases, which will be mentioned in the results.

The Gaussian distribution (normality) of the residuals and their homogeneity of variance linearity of means that are essential in the performance of mixed linear models were checked by observing the distribution of residues. The simulate option (SIM) by $\alpha = 0.05$ was applied to find solutions and make adjustments for multiple pair-wise comparisons between levels of the same factor.

3.7 Uncertainty and sensitivity analysis

The sensitivity analysis should be performed to find the reliability of the data and the effects of uncertainties in data gathering, calculations and allocation on the results as recommended by ISO standards (14044, 2006). Covariance analysis was performed on the statistical analysis of the model used for dairy data as a sensitivity analysis. However, the following sensitivity analysis was used to find the impact of the energy sources on feedstuff production and, thereafter, on the energy intensity of milk production. The methodology used in this study to assess the impact of the errors was the Gaussian error impact assessment. According to this method, the uncertainty of a function (F) to its variables (x_i) is described as follows (Huggins, 1991):

$$F = f(x_1, x_2, \ldots, x_n) \qquad \text{Equation 19}$$

$$F = \mu_F + u_F \qquad \text{Equation 20}$$

In which μ_F is the mean value of function F and u_F is its uncertainty. The u_F term is calculated according to the uncertainty of the variables (u_x) as follows:

$$u_F = \pm\sqrt{\sum_{i=1-n}\left(\frac{\delta F}{\delta x_i} \times u_{x_i}\right)^2} \qquad \text{Equation 21}$$

The uncertainty of u_x is calculated in the same way. In this study, the energy input is the sum of the energy inputs from different sources. The energy input from each source is then found by multiplying the amount (a) by the energy equivalent (b). Therefore:

$$x_i = a \times b \qquad \text{Equation 22}$$

$$x_i = \mu_{x_i} + u_{x_i} \qquad \text{Equation 23}$$

$$u_{x_i} = \pm\sqrt{(b \times u_a)^2 + (a \times u_b)^2} \qquad \text{Equation 24}$$

The uncertainty of *a* and *b* are determined by measuring instrument errors, accepted error in data gathering, assumptions, and so forth, according to the condition of each study. In this study, the acceptable error for data gathering was 10%. A sensitivity analysis was performed on for fuel and fertiliser consumption, for the N fertiliser energy equivalent uncertainty in the feedstuff farms, and for the feedstuff intake and direct energy consumption uncertainty on the dairy farms.

4 Results

4.1 Energy efficiency in feedstuff production

4.1.1 Energy input analysis

According to the results, the energy input per area for maize corn production was the highest, at 51,500 MJ ha^{-1} (figure 10, annex 1.1). For the other products, the energy input ranged between 36,800 MJ ha^{-1} (spring maize silage) and 28,000 MJ ha^{-1} (alfalfa). For all investigated crops except alfalfa, fertilisation was the single operation with the highest energy input, followed by irrigation. The high energy input from fertilisation was caused by the high energy demand for N fertiliser production. Within the maize corn production, energy input from fertilisers and their spread was 34% of the total energy input, of which 88% of the energy input came from the consumption of 200 kg ha^{-1} N fertiliser. Irrigation made up 22% and spraying operations accounted for 10% of the total energy input, which were the operations with the next highest energy input for maize corn production. In the spring maize silage, harvest and transportation of the highest amount of fresh matter yield (75 t ha^{-1}) had 19% of the total energy input. In addition, two instances of ploughing and three rounds of using of cultivator caused a high energy input in the form of machinery operations. In wheat, 150 kg ha^{-1} N fertiliser consumption (50% more than that of spring maize silage) and the spraying requirement caused the same extra energy input as from repeated machinery operations in spring maize silage. Summer maize silage or secondary maize silage cultivation had a short growing period (July-October) and was cultivated in a 2,000 ha quantity after the cereal or rapeseed harvest. The reduced energy input in summer maize silage in comparison to spring maize silage resulted from the exclusion of manure spreading, less repetition of the cultivator operation (only one) and a nearly 50% reduction in fresh matter yield and ensuing energy input from the transportation of summer maize silage production. Because summer maize silage was cultivated after a different prior crop, no energy input from manure spreading from the previous cultivation was allocated to summer maize silage. For all feedstuffs other than summer maize silage and barley, the energy input from manure spreading ranged between 4% (maize corn) and 8% (alfalfa) of the total energy input with the same amount per area (2,240 MJ ha^{-1}).

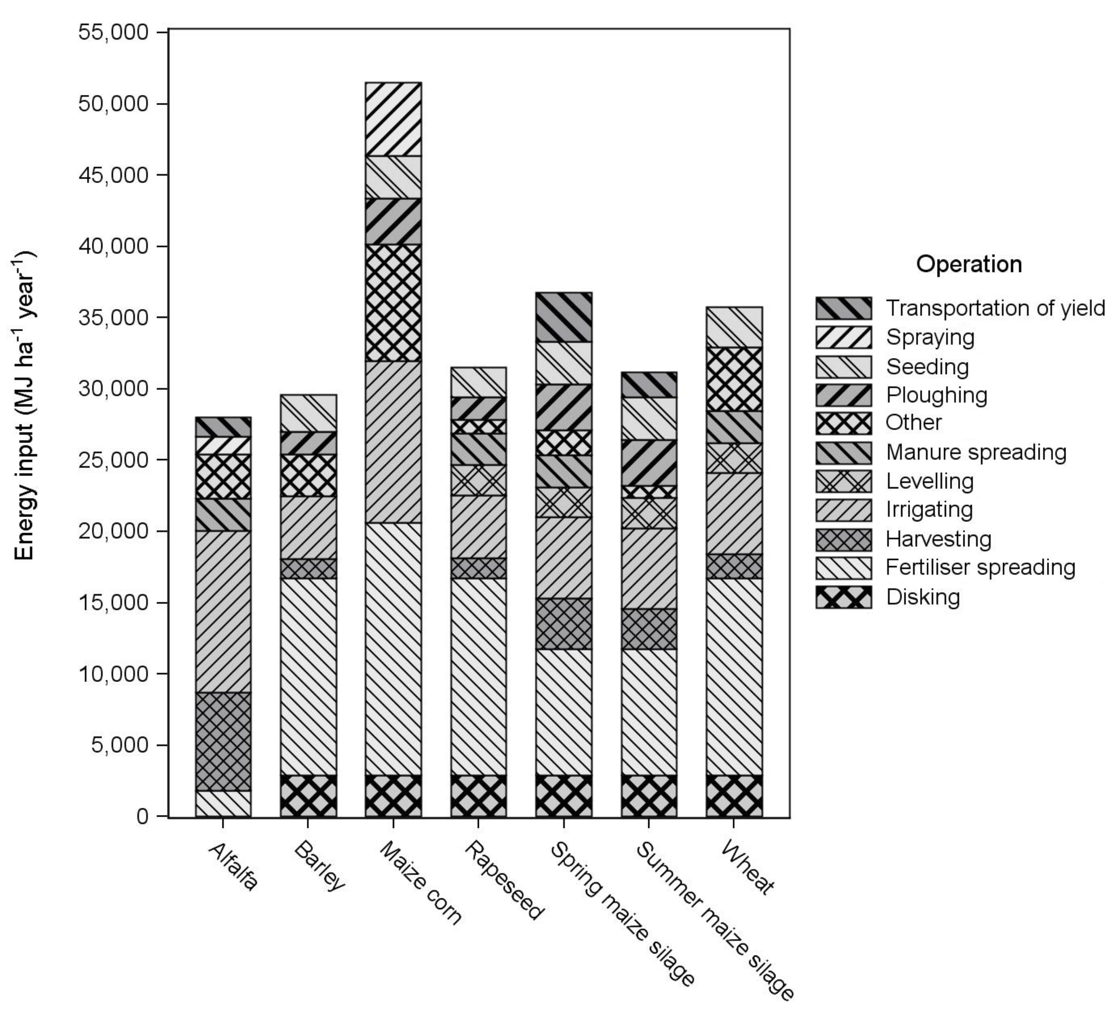


Figure 10 Energy input in the investigated crop production (MJ ha^{-1} yr^{-1}) from machinery operations including energy from materials, fuels and machines. [a b]

[a] Operations with an energy input of less than 5% of the total energy input were shown as Other".

[b] For summer maize silage, the yield was not yearly because it was cultivated as a secondary product.

No manure spreading was reported for barley production. Barley fertilisation comprised 48% of the total energy input. In alfalfa production, the energy input from irrigation was the highest, with 40% of the total energy input. This high share of the energy input came from high water consumption (18,000 m^3 ha^{-1}) as a result of flooding irrigation system. A harvest operation with 25% of the total energy input was the next biggest share of energy input, which resulted from five harvests per year and required three individual machinery operations (mower, rake, and baler). Operations with a share of less than 5% of the total energy input for each product were merged together as "Other" operations to limit the number of operations. Therefore, as an example, the spraying operation in this figure is only visible for alfalfa and maize corn production, with 5% and 10% of their total energy inputs, respectively.

The energy input from different sources and their proportion of the total energy input are shown for each investigated product in figure 11 (according to annex 1.2). The energy input from fertiliser was the biggest or second biggest energy source (maize silage) in total energy input, except for alfalfa, which had the lowest N fertiliser requirements. Fuel consumption during machinery operations was the main source of energy input in the production of maize silage, and it was the second main source of energy input for the other crops. In both maize silage productions, the diversity of machinery operations and the high volume and mass of the fresh matter yield caused high energy consumption during harvest and transfer. Thus, the fuel had the highest share of the energy input for both products.

Regarding the high volume of water consumption, irrigation was the third main source of energy input besides the fertilisers and fuel in most crops. With approximately 18,000 m^3 ha^{-1} water, irrigation caused the highest single energy input in alfalfa and in maize corn production, with nearly the same energy input as that of fuel consumption. Irrigation and fuel were the two dominant energy input sources in alfalfa, which were responsible for 73% of the total energy input. The energy inputs from machinery, seed, manure and pesticides were considerably less than the three dominant sources, except in alfalfa, in which energy input from fertilisers was very low. The energy input from pesticides was relatively high only in maize corn production. For the other products, energy input from pesticides was very low or zero for both maize silage products.

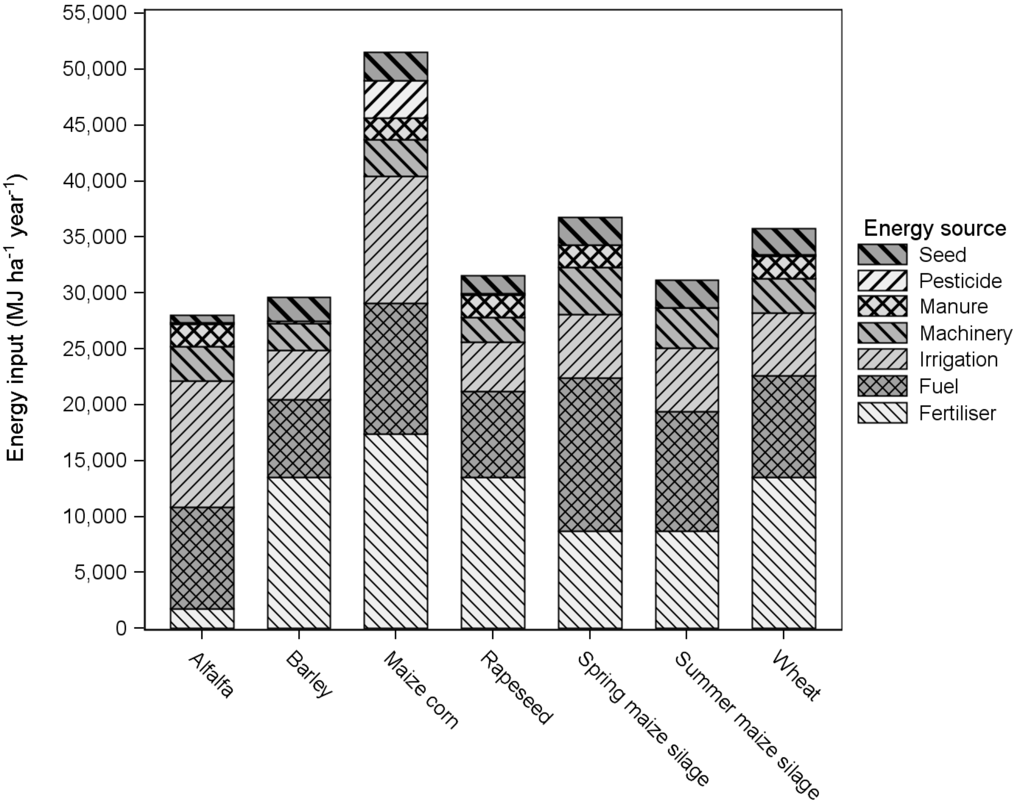


Figure 11 Energy input in the production of the investigated crops according to different sources (MJ ha^{-1} yr^{-1}).[a]

[a] For summer maize silage, the yield was not reported annually because it was cultivated as a secondary product.

4.1.2 Energy output (yield) of feedstuff production

Table 17 summarises the material yields and energy yields (energy output) of the investigated feedstuffs from Moghan Company. This table shows the fresh matter (FM) and dry matter (DM) yield of the crops as well as the calculated energy yield of each feedstuff farm in the HHV, the MEV and the NEL. Spring maize silage achieved the highest fresh and dry matter yield with 75,000 and 15,000 kg ha^{-1}, respectively, as well as the highest energy yield for all three energy calculations. In contrast, rapeseed gave the lowest and barley (grain and straw) yielded second lowest in all categories. Summer maize silage with 35,000 kg ha^{-1} FM and alfalfa with 12,000 kg ha^{-1} FM were the next crops with high FM yields. However, the wheat crop had higher DM yield than summer maize silage and alfalfa, considering the grain and straw yield together as two useful products. Following the spring maize silage, wheat (grain and straw) and alfalfa were the second and third highest, respectively, for all energy yield categories. Within the category of NEL yield, maize corn and summer maize silage both changed their positions (to fourth and fifth, respectively). However, there was no large difference between their MEV and NEL yields. By using straw (by-product) as a feedstuff and comparing its MEV yield with the MEV yield of grain (main product), about one fourth of the total MEV yield of wheat and barley cultivation belonged to the straw yield. Based on the NEL for both crops, nearly 22% of the total yield comes from straw.

Table 17 Yearly yield and energy yield from investigated crops in Moghan Company.

	Alfalfa	*Barley*		*Maize corn*	*Rapeseed*	*Spring maize silage*	*Summer maize silage* [a]	*Wheat*	
		Grain	Straw					Grain	Straw
FM yield (kg ha^{-1})	12,000	4,000	2,400	7,000	3,000	75,000	35,000	7,000	4,900
DM yield (kg ha^{-1})	9,600	3,200	1,920	5,600	2,550	15,000	7,000	5,950	4,165
HHV yield (MJ ha^{-1})	174,720	58,880	35,136	104,720	80,325	285,000	133,000	108,290	77,052
MEV yield (MJ ha^{-1})	78,720	39,040	13,056	73,360	44,625	160,500	74,900	77,350	24,990
NEL yield (MJ ha^{-1})	48,000	24,960	7,296	47,040	27,285	96,000	44,800	49,386	14,161

[a] Summer maize silage was cultivated as the secondary product in between other crops.

4.1.3 Energy efficiency indicators in feedstuff production

The energy input from common operations between straw and grain was 28,600 MJ ha^{-1} of barley and 33,900 MJ ha^{-1} of wheat production (annex 1.1). This energy was allocated to straw and grain in each production by using the energy yield information in table 17. Three measures of energy yield (the HHV, MEV and NEL) were used separately in this manner.

The energy input for grain transportation was 193 MJ ha^{-1} for barley and 285 MJ ha^{-1} for wheat production. Barley straw bailing and transportation required 763 MJ ha^{-1} and wheat straw required 1,556 MJ ha^{-1}. Using this information, the energy efficiency indicators for barley and wheat production were calculated and are shown in table 18.

According to table 18, the OIR indicators for barley and wheat production with based on HHV were 3.18 and 5.19 MJ MJ^{-1}, respectively, when grain and straw were taken into account. They were significantly more than the 2.04 and 3.17 MJ MJ^{-1} for barley and wheat, respectively, when only the grain yield was considered. The EI was 9.01 MJ kg^{-1} barley grain and 5.74 MJ kg^{-1} wheat grain when only the grain yield was considered. When both grain and straw were taken into consideration, the EI was much lower. Based on HHV, the calculated EIs of straw and grain were nearly same (at 5.66 and 5.97 MJ kg^{-1} for barley straw and grain, respectively, and 3.38 and 3.76 MJ kg^{-1} for wheat straw and grain, respectively). Using an energy input allocation for grain and straw according to their MEV or NEL resulted in a significant difference between the EIs of grain and straw. This difference was caused by the greater difference between the MEVs or the NELs of grain and straw. In other words, the metabolisable energy of straw is much lower than that for grain; therefore, the majority of the energy input was allocated to the grain rather than to straw. The difference between the MEV-based and NEL-based EI was slight for both the straw and grain of both crops.

The efficiency indicators as calculated for alfalfa, rapeseed, maize corn and maize silage in three energy yield calculations are shown in table 19. These products have no by-product and, therefore, the energy input allocation for the resulting DM yield or energy yield was straightforward.

In the following section, the feedstuffs are compared based on MEV for efficiency indicators because they are used for all the cattle categories (lactating and non-lactating). In addition, the energy yields for barley and wheat are the sum of the energy for straw and grain, as both were used as feedstuff. According to table 18 and table 19, the spring maize silage was the best feedstuff out of all the crops investigated for every efficiency indicator and all three energy calculations. For spring maize silage, the OIR was 4.36 MJ MJ^{-1} MEV, the EI was 2.45 MJ kg^{-1} DM and the NEY was 124 GJ ha^{-1}. Wheat (grain and straw) was the second most advantageous crop due to its higher OIR at 2.86 MJ MJ^{-1} MEV, followed by alfalfa with 2.81 MJ MJ^{-1} MEV and summer maize silage with 2.40 MJ MJ^{-1} MEV. The OIR of maize corn and rapeseed was the lowest with 1.42 MJ MJ^{-1} MEV.

The energy intensity was the most important indicator in this study because this measure was used to calculate the cumulative energy demand in milk production. Alfalfa was the second best crop for lower EI with 2.92 MJ kg^{-1} DM, followed by wheat with 4.35 MJ kg^{-1} DM and summer maize silage with 4.45 MJ kg^{-1} DM. The highest EI was found for rapeseed at 12.36 MJ kg^{-1} DM.

Wheat was the second highest crop for the NEY with 66.6 GJ ha^{-1} (MEV), which was higher than that for alfalfa with 50.7 GJ ha^{-1}. The NEY indicator was the lowest in rapeseed production with 13.1 MJ ha^{-1}.

The labour energy productivity was another calculated energy indicator. The spring maize silage was the best crop, with an MEV-based LEP of 4.66 GJ h^{-1}. It was followed by wheat with an LEP of 2.88 GJ h^{-1}. Alfalfa had the lowest LEP with 1.24 GJ h^{-1}. The flooding irrigation system used in the Moghan Company requires approximately 2 hours of labour per hectare for each irrigation incident. The high amount of irrigation water needed for alfalfa and maize corn production (18,000 m^3 with in average of 8 instances of irrigation per year) was the main source of the labour requirements in alfalfa and maize corn. The manual loading of the bales of alfalfa and straw into trucks also required labour hours.

Table 18 Energy efficiency indicators for DM wheat and barley with the energy yield calculated based on HHV, MEV and NEL.

Product	*Barley*				*Wheat*			
Useful yield	Only grain	Grain and straw			Only grain	Grain and straw		
Energy yield base	HHV	HHV	MEV	NEL	HHV	HHV	MEV	NEL
Energy output/input ratio (OIR) MJ MJ^{-1}	2.04	3.18	1.76	1.09	3.17	5.19	2.86	1.78
Energy intensity (EI) MJ kg^{-1} DM	9.01				5.74			
Grain [a]		5.66	6.76	6.98		3.38	4.35	4.47
Straw [a]		5.97	4.13	3.77		3.76	2.36	2.19
Energy productivity (EP) kg MJ^{-1} DM	0.11				0.17			
Grain [a]		0.18	0.15	0.14		0.30	0.23	0.22
Straw [a]		0.17	0.24	0.27		0.27	0.42	0.46
Net energy yield (NEY) 1000 MJ ha^{-1}	30.1	64.4	22.5	2.7	74.1	150	66.6	27.8
Labour energy productivity (LEP) 1000 MJ h^{-1}	2.99	3.77	2.09	1.29	4.40	5.21	2.88	1.79

[a] Allocated energy input.

Table 19 Energy efficiency indicators for DM feedstuffs with the HHV, MEV and NEL measures of energy yield.

Product	*Alfalfa*			*Maize corn*			*Rapeseed*			*Spring maize silage*			*Summer maize silage*		
Energy yield basis	HHV	MEV	NEL	HHV	MEV	NEL	HHV	MEV	NEL	HHV	MEV	NEL	HHV	MEV	NEL
Energy output/input ratio (OIR) MJ MJ^{-1}	6.23	2.81	1.71	2.03	1.42	0.91	2.55	1.42	0.87	7.75	4.36	2.61	4.27	2.40	1.44
Energy intensity (EI) MJ kg^{-1} DM	2.92	2.92	2.92	9.19	9.19	9.19	12.36	12.36	12.36	2.45	2.45	2.45	4.45	4.45	4.45
Energy productivity (EP) kg MJ^{-1} DM	0.34	0.34	0.34	0.11	0.11	0.11	0.08	0.08	0.08	0.41	0.41	0.41	0.22	0.22	0.22
Net energy yield (NEY) 1000 MJ ha^{-1}	147	50.7	20.0	53.2	21.9	- 4.5	48.8	13.1	- 4.2	248	124	59.2	102	43.7	13.6
Labour productivity (LEP) 1000 MJ h^{-1}	2.75	1.24	0.76	2.43	1.70	1.09	3.82	2.12	1.30	8.27	4.66	2.79	4.58	2.58	1.54

4.1.4 Energy intensity of feedstuffs consumed in dairy farms

Energy consumption during the production (i.e., energy intensity) of feedstuffs was an essential piece of information for the energy investigation of dairy farms. The energy intensity of the crops in this study and allocated energy for their by-products are summarised in table 20.

Table 20 Energy intensity (EI) of the investigated feedstuffs and allocated energy intensity to their by-products when used as feedstuff.

Feedstuff	*EI* *MJ kg^{-1} DM*	*Feedstuff*	*EI* *MJ kg^{-1} DM*
Alfalfa hay	2.92	Rapeseed (40% oil [d])	12.36
Barley grain	6.76 [a]	Rapeseed meal	9.25
Barley straw	4.13 [a]	Wheat grain	4.35 [a]
Maize corn	9.19	Wheat bran	3.62 [c]
Maize silage	3.42 [b]	Wheat straw	2.36 [a]

[a] EI allocated based on the MEV ratio of grain and straw and consumed energies in their production; [b] Weighted average of the results for summer and spring maize silage in this study according to cultivation area and yield; [c] Allocated EI based on the MEV ratio of grain and bran.

For the other feedstuffs not investigated in this study, the results of other published studies were used. The energy intensity of these feedstuffs and the energy allocated to their by-products are summarised in table 21. For feedstuffs for which there was not enough information about production energy (e.g., fish meal, fat powder, poultry, meat and bone meal), their HHVs were used to calculate their EI.

Table 21 Energy intensity of feedstuffs not investigated in this study.

Feedstuff	*EI* *MJ kg^{-1} DM*	*Feedstuff*	*EI* *MJ kg^{-1} DM*
Beet (sugar beet)	3.28 [a]	Soya bean	9.17 [d]
Beet pulp	2.92 [b]	Soya bean meal	7.96 [b]
Beet molasses	3.12 [b]	Sunflower seed	8.49 [e]
Cottonseed (with linter)	9.59 [c]	Sunflower meal dehulled	3.88 [b]
Cottonseed hulls & gin trash	4.38 [b c]	Tomato	11.9 [f]
Cottonseed meal	7.79 [b c]	Tomato pomace	11.5 [b]

[a] Derived from Erdal et al. (2007); [b] Allocated energy intensity based on the MEV ratio of product and by-product; [c] Calculated by substitution (see section 0); [d] Mandal et al. (2002); [e] Uzunoz et al. (2008); [f] Rezvani Moghaddam et al. (2011).

For the energy intensity of the fat powder, fish meal, meat and bone meal, and poultry offal (which have not been published anywhere), their HHV was used as the energy input in this study (according to table 10, they had values of 37.9, 20.9, 16.7 and 22.7 MJ kg^{-1} DM, respectively). The HHV-based OIR indicator was therefore assumed to be equal to 1.

4.1.5 Sensitivity analysis of feedstuff production

Different figures can be found for the N fertiliser production energy input, depending on the state of the production technique. The amount of fertiliser, fuel and irrigation water can also vary from farm to farm. Therefore, a sensitivity analysis was carried out for these parameters. A sensitivity analysis was performed by assuming 10% uncertainty. Table 22 shows the effects of this uncertainty on the energy intensity of the feedstuffs in the study. The uncertainty effect of N fertiliser (either in consumption or in consumption and energy equivalent together) on the alfalfa production EI was very low (0.30% and 0.34%, respectively), and the effect of the uncertainties in diesel consumption and irrigation water was rather high (3.4% and 4.1%, respectively). For the feedstuffs other than alfalfa, the uncertainty effect for N fertiliser was stronger, especially for barley (uncertainty at 4.0% for N fertiliser consumption and 5.7% for N fertiliser consumption and simultaneously its equivalent). The uncertainty in diesel consumption, besides alfalfa, had its strongest effect on the EI of maize silage.

Table 22 Sensitivity analysis of the HHV energy intensity of products.

Uncertainty source	*Uncertainty (%)*	*Sensitivity of the EI indicator of feedstuff (%)*						
		Alfalfa	Barley grain	Maize corn	Rape-seed	Spring maze silage	Summer maize silage	Wheat grain
N fertiliser consumption or energy equivalent	10	0.30	4.00	3.00	3.70	2.00	2.50	3.50
N fertiliser consumption and energy equivalent	10	0.34	5.66	4.35	5.26	3.27	3.60	4.88
Diesel consumption	10	3.41	2.33	2.10	2.41	3.72	3.41	2.43
Irrigation water	10	4.12	1.62	2.20	1.44	1.60	1.81	1.62

4.2 Energy efficiency of the dairy farms

4.2.1 An overview on the investigated dairy farms

The investigated dairy farms were located in 4 regions of East and West Azarbaijan and Zanjan provinces in north-western Iran. Data were collected for 3 years, namely 2008, 2009 and 2010. In region 1 in East Azarbaijan, there were 3 dairy farms, and in region 2 in the same province, 12 dairies were investigated. Eight dairy farms in region 3 in West Azarbaijan were studied. Finally, only one dairy farm in region 4 of Zanjan province was analysed. Table 23 shows the main specifications for the investigated dairy farms over the three years of investigation.

Twenty of the 24 investigated dairy farms had less than 50 (heads) cows, 2 had between 50 and 99 (heads) cows and 2 farms had 100 (heads) or more cows. The smallest dairy farm was dairy 9 in region 2, with 20 (heads) cattle (9 cows) during the first years of investigation. Dairy 24 in region 4 was the biggest, with 645 (heads) cattle (363 cows) in 2010. There was no significant difference between the cow number in dairies from regions 1-3 or during the investigation years, except for dairies 9, 12 and 16, which had a substantial change in the cow number during the investigation years. The average cow number for region 1 was 24±15 heads; for region 2, it was 41±7 heads; and for region 3, it was 30±9 heads. On average, 35±21 (heads) cows were in the dairies in regions 1-3; dairy 24 had 360±3 (heads) cows, and dairy 8 had 102±2 (heads) cows.

In most of the dairy farms, bull cattle and heifers were kept beside the cows. It was only in dairies 22 and 24 that the male calves were sold some weeks after birth. Therefore, the herd size of dairy farms was usually more than two times the cow number of the herd.

According to table 23, only 9 dairies had feedstuff farm areas with approximately 1 to 10 ha, mostly under alfalfa cultivation. The grazing program in the feedstuff farm was the only one there, and thus, the required feedstuffs were bought from markets.

Table 23 Dairy farm specifications for the three investigation years.

			Dairy specifications									
			2008			2009			2010			
Dairy farm no.	*Region no.*	*Province*[a]	Cow number[b] (head)	Herd size[c] (head)	Milk yield[d] (kg yr^{-1} head^{-1})	Cow number[b] (head)	Herd size[c] (head)	Milk yield[d] (kg yr^{-1} head^{-1})	Cow number[b] (head)	Herd size[c] (head)	Milk yield[d] (kg yr^{-1} head^{-1})	*Feedstuff farm (ha)*[e]
1	1	E. A.	20	44	7,520	19	43	7,230	20	41	7,280	0
2	1	E. A.	21	51	7,050	22	49	7,000	23	59	6,920	0
3	1	E. A.	23	58	6,320	26	59	6,010	26	54	6,080	0
4	2	E. A.	62	142	7,050	65	138	7,230	63	143	7,230	0
5	2	E. A.	35	74	4,470	35	70	4,660	38	91	4,810	0
6	2	E. A.	47	111	7,550	48	116	7,580	50	112	7,600	0
7	2	E. A.	25	61	6,690	25	60	6,970	25	64	7,250	3
8	2	E. A.	100	252	8,210	103	256	8,060	104	256	8,150	0
9	2	E. A.	9	20	6,080	9	20	6,240	18	32	5,860	0
10	2	E. A.	25	52	5,840	21	41	5,450	20	35	5,580	5
11	2	E. A.	12	30	7,850	12	29	8,240	12	29	7,750	0
12	2	E. A.	22	34	5,220	15	32	5,240	12	22	5,560	0
13	2	E. A.	33	79	8,060	34	81	7,990	41	99	7,800	1
14	2	E. A.	70	163	7,540	70	177	7,800	70	164	7,870	0
15	2	E. A.	28	66	6,490	26	98	6,370	25	58	6,500	0
16	3	W. A.	35	78	3,860	22	45	4,690	20	48	4,970	4
17	3	W. A.	50	103	5,480	45	104	5,470	40	91	5,700	10
18	3	W. A.	40	105	8,150	40	102	8,310	43	107	7,900	4
19	3	W. A.	30	55	7,160	34	79	6,990	37	87	7,000	6
20	3	W. A.	30	64	5,150	30	76	4,990	30	68	5,160	3
21	3	W. A.	20	41	4,140	21	46	4,050	20	42	4,390	5
22	3	W. A.	35	55	6,620	36	71	6,560	38	73	6,230	0
23	3	W. A.	35	75	7,020	35	84	6,760	35	77	6,890	3
24	4	ZA	360	512	8,050	356	613	8,150	363	645	8,020	0

[a] *E. A.: East Azarbaijan; W. A.: West Azarbaijan; ZA: Zanjan*
[b] *The number of dairy cattle in the dairy farm*
[c] *The total number of cattle in the dairy farm*
[d] *ECM yield*
[e] *Area of own feedstuff production*

4.2.2 Milk production in the dairy farms

The ECM yield of the investigated dairy farms was 6,585±1,221 kg cow^{-1} yr^{-1} on average. The yield varied between 3,861 kg cow^{-1} yr^{-1} and 8,317 kg cow^{-1} yr^{-1}. The ECM yield distribution in these regions is shown in figure 12. The ECM yield was calculated according to the average milk protein and fat content of the dairy farms, which were measured monthly and provided by the farms. The milk protein content of all investigated dairy farms ranged between 2.98% and 3.30%, and the fat content was between 3.30% and 3.90%.

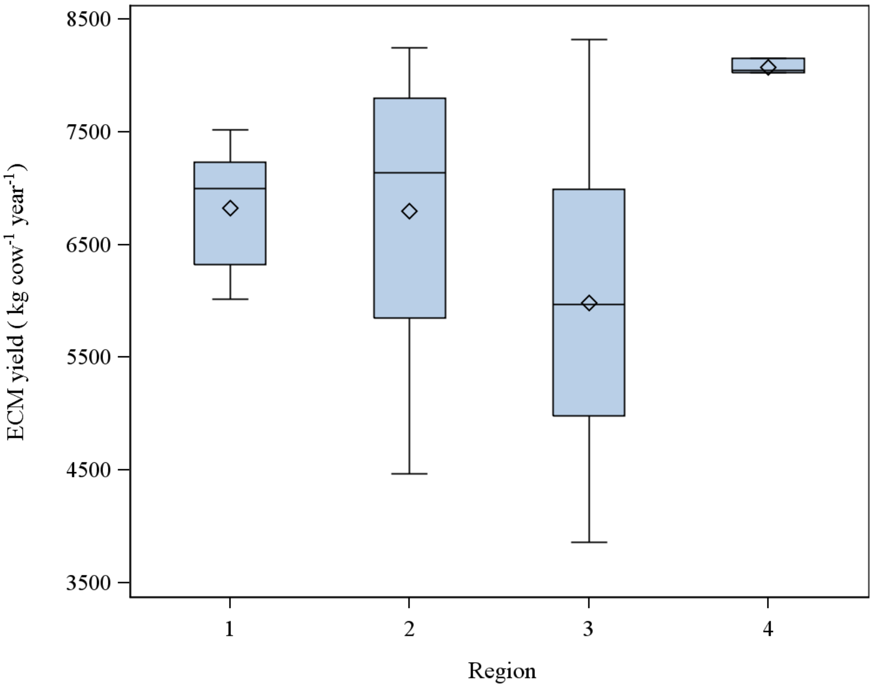


Figure 12 Box plot of dairy farm ECM yield (kg cow^{-1} yr^{-1}) for regions 1-4.

Statistical analyses of the ECM yield (kg cow^{-1} yr^{-1}) and the protein and fat contents of the fresh milk produced in the dairies were performed using the model defined in the methodology chapter (equation 18). The covariance analysis results are shown in table 24.

Table 24 Covariance analysis of the protein and fat content in fresh milk and the ECM yield of cows from investigated dairies.

Effect	*Analysed parameters*									
		Protein content			*Fat content*			*ECM yield (kg cow^{-1} yr^{-1})*		
	Num DF	Den DF	F Value	Pr > F	Den DF	F Value	Pr > F	Den DF	F Value	Pr > F
Year	2	40.1	0.10	0.9014	38.3	0.02	0.9779	34.3	0.15	0.8650
Region	3	20.1	0.97	0.4262	20	3.51	0.0341	21.6	3.86	0.0237
Year × Region	6	40.2	0.68	0.6660	38.4	0.31	0.9291	34.1	0.61	0.7231
Cow number	1	24.9	3.24	0.0839	30.9	2.05	0.1617	54.6	9.64	0.0030
ECM (kg cow^{-1} yr^{-1})	1	26.1	2.62	0.1178	34.2	2.01	0.1654	-	-	-

According to the statistical analysis for regions 1-4, the protein content was not significantly affected by the year, region, ECM yield and cow number in the dairies. The mean protein content of the fresh milk produced in regions 1-4 was 3.14±0.07%. The difference in fat contents between the regions was significant at a level of 5% in the F-test. However, with the adjusted probability made to account for multiple pair-wise testing, this effect was no longer significant because this particular simulation test adjusted the estimations for the single dairy in region 4 (dairy 24). There was a need to have at least 3 dairy farms in a region for the regression estimation (in covariance analysis). Because a regression estimate was impossible for region 4, the covariance analysis was not working properly and the model adjustment for dairy 24 made the difference between other dairy farms insignificant. To find a solution for this problem, dairy farm 24 (and thus region 4) was excluded from all further statistical analyses. After excluding dairy 24, the model was tested for the fat content of milk produced in regions 1-3. The results showed that region 1 had a mean milk fat content of 3.71±0.08%, which was different from region 2 with 3.49±0.05% at a significance level of 0.05. Region 3 had a milk fat content of 3.57±0.04% and was not different from regions 1 and 2. The fat content of the milk produced in dairy 24 was 3.49±0.01%.

The selected model (equation 18) yielded a significant difference between the ECM yield for the regions and the number of cows per farm (table 24).

With an improved model (described in table 25), the interaction effect of the region and cow number was analysed. The results showed a significant effect on the ECM yield only for the interaction effect between the cow number and the region (table 25).

$$\mathrm{ECM\ (kg\,cow^{-1}\,yr^{-1})}_{ij} = \mu + \mathrm{Y}_i + R_{\mathrm{j}} + (\mathrm{Y} \times \mathrm{R})_{\mathrm{ij}} + \mathrm{n} \times \mathrm{C} + r_{\mathrm{j}} \times \mathrm{C} + f + \mathrm{e}_{\mathrm{ij}} \qquad \text{Equation 25}$$

Where r_j is the estimated regression slope for each region. Other elements are described by equation 18 (p. 67).

Table 25 Covariance analysis of the ECM yield of cows in the investigated dairies.

	Tests of fixed effects for ECM yield			
Effect	Num DF	Den DF	F Value	Pr > F
Year	2	36	0.54	0.5894
Region	2	47.3	0.54	0.5846
Year × Region	4	35.7	0.81	0.5252
Cow number	1	39.4	0.62	0.4371
Cow number × Region	2	44.3	5.85	0.0056

The estimated intercepts for the region effects and the regression slopes for each region were analysed with the improved model (table 25). The significant and meaningful effect results are given in table 26 (see annex 2.1 for complete solutions).

Table 26 Estimated intercept and slopes for the tested model between the region and the number of cows per farm on the ECM yield.

	Solutions for Fixed Effects	
Effect	*Estimate*	*Standard Error*
Fixed Effects (Intercept)		
Region 1	7,054.50	2,146.29
Region 2	6,943.50	557.56
Region 3	7,787.98	607.64
Regressions (slopes)		
Cow number × Region (r_1)	- 12.81	86.69
Cow number × Region (r_2)	- 2.85	9.79
Cow number × Region (r_3)	- 53.38	11.07

The average ECM yield after the model (table 25) was 6,661±1,358 kg cow^{-1} yr^{-1} for region 1, 6,813±398 kg cow^{-1} yr^{-1} for region 2, and 5,901±584 kg cow^{-1} yr^{-1} for region 3. For dairy 24 (region 4) the average ECM yield after the model was 8,073±67 kg cow^{-1} yr^{-1} during the three years of investigation.

Figure 13 graphically demonstrates the ECM yield depending on the number of dairy cows per farm, including estimated linear trend lines for regions 1-3. Although the trend lines show a negative slope, the limited number of the farms in the regions 1-3 (9-104 head cows) and between regions does not allow a properly interpretation of the effect of the number of cows on ECM yield.

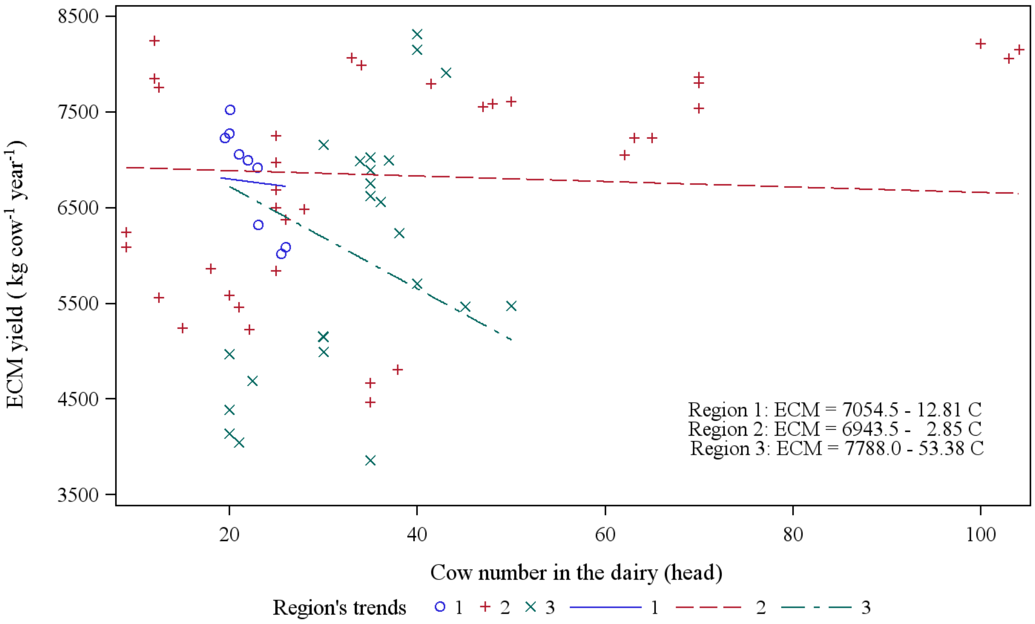


Figure 13 Scatter plot and estimated linear trends of ECM yield (kg cow^{-1} yr^{-1}) versus cow number for regions 1-3.

The calving interval (lactating days plus a 2 month dry period) was between 355 and 400 days. The calving interval was 394.4±5.7 days for region 1, 371.8±2.9 days for region 2, and 377.5±3.5 days for region 3. Finally, the calving interval for dairy 24 was 370±1.0 days. There was a significant difference between regions 1 and 2 (Adj. P=0.006) but not between these regions and region 3.

4.2.3 Indirect energy input by buildings and machines

Buildings

The keeping area of the dairy farm generally consisted of the stall building, an open farmyard area outside the stall, storage buildings, a milking parlour, silos and a labour house. The dairy farms varied in the given building areas, amount of roofed and non-roofed area and building materials. Stall walls and roofs were mostly made of bricks with metal or woody pillars and sometimes of corrugated galvanised sheets. Roofed farmyard area was mostly covered with corrugated galvanised sheets. Mangers and the floors of stalls and farmyards were made of concrete. A milking parlour was found only in the large-scale farms. In the small farms, the cows were milked when standing in the stall with small mobile milking machines (single or double). Feedstuffs were stored in bulk or in sacks, except for dairy 24, which had some vertical silos. The maize silage was stored in underground concrete silos.

The allocated roofed area per cow was 14.4±2.2 m^2 in region 1, 14.8±1.1 m^2 in region 2, 9.5±1.3 m^2 in region 3, and 10.9±0.6 m^2 in region 4. Only the difference between region 2 and region 3 was significant ($\alpha=0.05$). The mean open area value in regions 1-3 was 53±28 m^2. The open area per cow was significantly dependent on the cow number. On average, dairies with a large number of cows had a lower open area per cow than the smaller ones. Nevertheless, the open area per cow in dairy 24 was 77±4 m^2.

The allocated energy input in the ECM from total energy embodied in the roofed area, non-roofed area and silos was 0.19±0.09 MJ kg^{-1}. The range was between 0.06 and 0.50 MJ kg^{-1}.

The reference model (equation 18, p. 63) was excluded for the ECM yield effect to find the best model for analysing the energy input from a building area (EI_B) in the ECM (MJ kg^{-1}) produced in the regions 1-3 as follows:

$$\mathrm{EI_B\ (MJ\ kg^{-1})_{ij}} = \mu + \mathrm{Y_i} + \mathrm{R_j} + (\mathrm{Y} \times \mathrm{R})_{ij} + \mathrm{p} \times \mathrm{C} + f + \mathrm{e_{ij}} \qquad \text{Equation 26}$$

The statistical analysis for this model showed a significant regional effect on the ECM energy input from the building area (α=0.05). The farm cow number was also a significant factor at a significance level of 0.01 (DF of 29.2). The solutions for this model are given in table 27.

Table 27 Estimated solutions for a model testing the effects of the region and number of cows in a farm on the energy input from a building area on milk (MJ kg^{-1} ECM).[a]

	Solutions for Fixed Effects	
Effect	*Estimate*	*Standard Error*
Fixed Effects (Intercept)		
Region 1	0.2304	0.04903
Region 2	0.3369	0.03795
Region 3	0.2282	0.03814
Regression (slope)		
Cow number (p)	- 0.0027	0.00077

[a] Only the intercepts of significant or meaningful effects are given.

The mean EI caused by the energy input from buildings (EI_B) was 0.13±0.05 MJ kg^{-1} ECM for region 1 and 0.24±0.02 MJ kg^{-1} ECM for region 2. For region 3, the EI_B was 0.14±0.03 MJ kg^{-1} ECM, and it was not different from region 1. The mean EI_B of region 2 was significantly different from regions 1 and 3. The regression trend for the cow number was slightly negative (table 27), i.e., EI_B slightly decreased with an increasing number of cows per farm. In dairy farm 24 (region 4), the EI_B was 0.18±0.01 MJ kg^{-1} ECM.

Machinery

The machines (present and in use) in the dairy farms, their power, mass and operating hours were different among the dairies. Nine dairies had stationary milking machines (i.e., a milking parlour); out of them, 7 dairies were located in region 2, one dairy was in region 3, and one farm was in region 4. There were 12 farms with a concentrated feed mixing machine. Eight dairy farms were in region 2, three were in region 1, and there was one dairy in region 4. The mixing machines were a combination of a mill, elevator and mixer with total electric power between 15 and 27 kW. Seventeen farms had a hay comminuter with a power range between 1.5 and 2.25 kW. Comminuters had their own electric power or tractor implement. Seven dairies had a milk cooler, with 3 in region 2, 3 in region 3 and 1 in region 4. All farms were using an electric or diesel engine water pump to supply their water requirement. Dairy 5 had no electricity supply and was using a diesel motor for 6 hours per day to support its electricity requirements. The excrement removal and feedstuff supply was mostly performed manually. However, 5 dairies in region 2, 2 dairies in region 3 and the only dairy in region 4 were using their tractors to transport feedstuffs inside the dairy or to remove excrement from the open area of the dairy. Dairy farm 24 had 7 tractors, and each one was used up to

2 hours per day. Other machinery included a sprayer to disinfect the farms, which was obligatory every month. With the exception of dairy 24, no ventilation facility was used.

The energy input from machinery per kg ECM was between 0.04 and 0.19 MJ. The mean value of EI_M for regions 1-3 was 0.09±0.01 MJ kg^{-1} ECM. The EI_M was the highest for dairy farm 24 (region 4), with 0.19 MJ kg^{-1} ECM. By analysing the allocated energy input (for region 1-3) from the indirect energy embodied in the machinery per kg ECM, no significant effect was detected for the regions of interest.

4.2.4 Direct energy input

The direct energy input sources in the dairy farms came from the consumption of diesel, natural gas and electricity. The dairies were using diesel, natural gas or both for heating and warming the water used in cleaning. Diesel was also used as a tractor fuel. The energy input from each source was calculated and summarised together. The allocated direct energy input (EI_D) in the resulting ECM was an average of 1.01±0.93 MJ kg^{-1}. The lowest and highest values were 0.60 and 2.83 MJ kg^{-1} (figure 14), respectively. The highest diesel consumption, observed in dairy 5 (region 2), was used to generate and supply electricity, and dairy 5 had the highest direct energy consumption for all milk production sites (the three dots, one for each year, can be seen in figure 14).

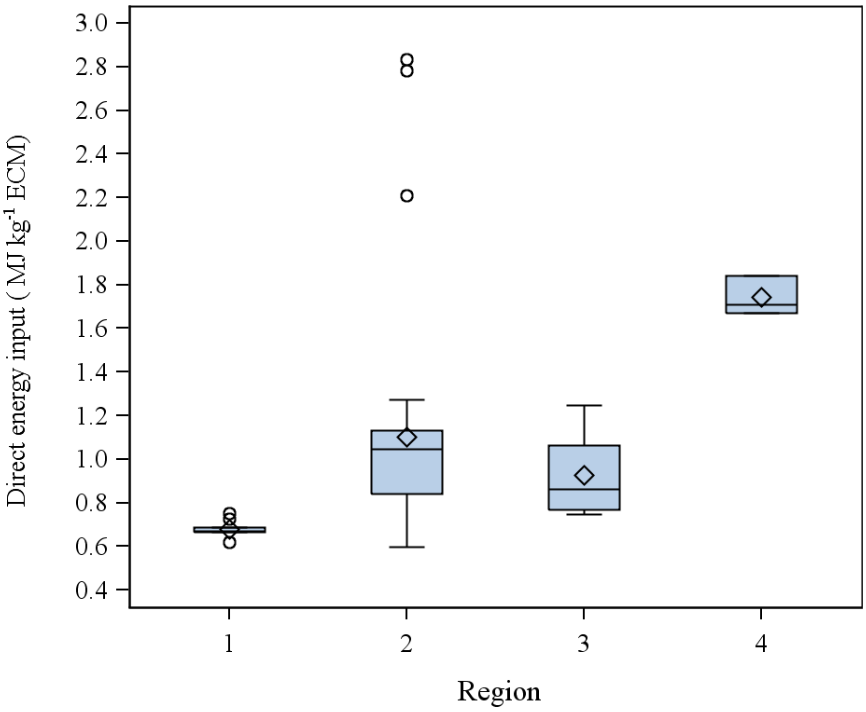


Figure 14 Box plot of the direct energy input in the ECM (MJ kg^{-1}) produced in the investigated dairy farms according to their regions.

The statistical model indicated that the mean value of the EI_D was 0.65±0.22 in region 1, 1.16±0.11 in region 2 and 0.86±0.14 MJ kg^{-1} ECM in region 3. In dairy farm 24 (region 4), the mean value of the EI_D was higher than in the other regions, with 1.74±0.09 MJ kg^{-1} ECM.

For statistical analysis of the EI_D interaction effect, the year and region from the reference model (equation 18, p. 63) were removed to yield a better fitted model. The statistical analysis for the new model showed a significant effect for the year and ECM yield on EI_D at a significance level of 0.05 (table 28).

Table 28 Covariance analysis of the direct energy input in ECM (MJ kg^{-1}).

	Tests of fixed effects for direct energy input			
Effect	Num DF	Den DF	F Value	Pr > F
Year	2	38.8	3.25	0.0494
Region	2	15.5	2.67	0.1005
Cow number	1	41.6	3.01	0.0900
ECM (kg cow^{-1} yr^{-1})	1	49.3	5.09	0.0285

The significant and meaningful solutions estimated for the tested model for EI_D are shown in table 29 (see annex 2.2 for the complete table). According to this table, there was a slight decrease in the EI_D from 2008 to 2010. The difference between the overall mean values of all farms was 0.91 MJ kg^{-1} ECM in 2008, 0.90 MJ kg^{-1} ECM in 2009 and 0.85 MJ kg^{-1} ECM in 2010. These results indicate that an approximately 7% reduction in energy input from direct energies occurred from 2008 to 2010. The difference between 2008 and 2010 was significant, but no difference was observed between 2009 and 2008 and 2010.

Table 29 Estimated solutions for the model testing the effects of the year, number of cows per farm and the ECM yield on the direct energy input for milk (MJ kg^{-1} ECM).[a]

	Solutions for Fixed Effects	
Effect	Estimate	Standard Error
Fixed Effects (Intercept)		
Year 1 (2008)	1.8201	0.3531
Year 2 (2009)	1.8006	0.3532
Year 3 (2010)	1.7541	0.3552
Regression (slope)		
ECM yield (E)	- 0.00011	0.000051

[a] Only the intercept of significant or meaningful effects is given.

According to table 29, a significant and reverse slope (trend) is estimated by the statistical analysis for the ECM yield effect on EI_D for regions 1-3. In other words, an increase in the ECM yield leads to a decrease in the EI_D. According to the intercept and estimated regression, an increase in the ECM yield per cow and the year from 6,000 to 7,000 kg could reduce the EI_D by 10%. The effect of the ECM yield on EI_D within the investigation years is shown in figure 15.

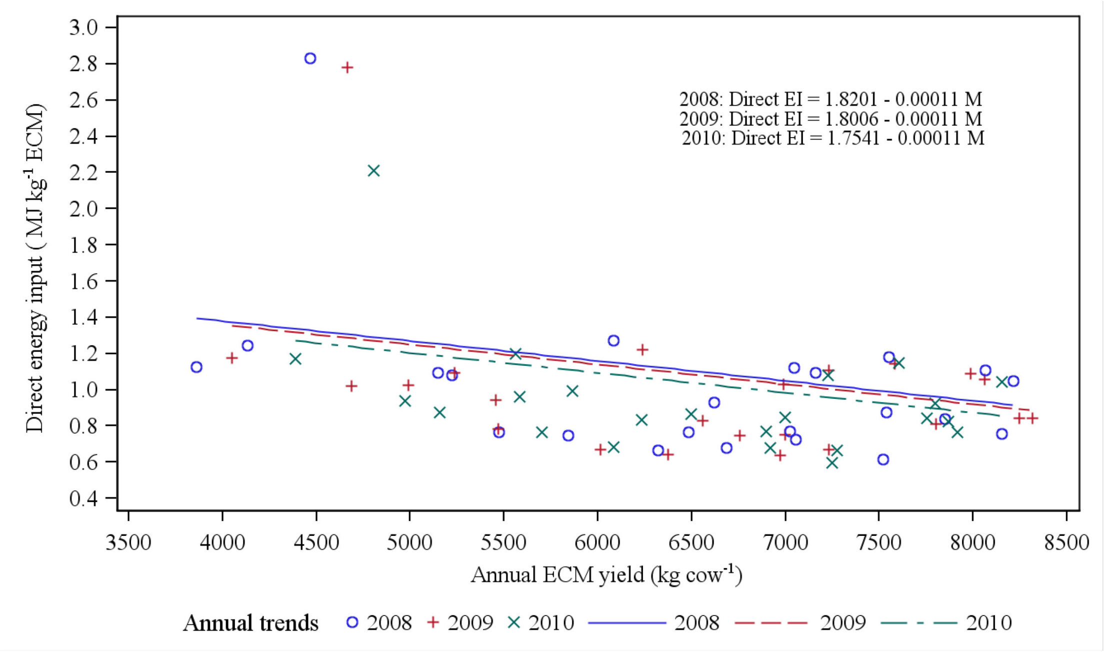


Figure 15 Scatter plot and estimated linear trends of the relationships between the ECM yield (kg cow^{-1} $year^{-1}$) and the direct energy input in its production (MJ kg^{-1} ECM) during the years of investigation.

No significant effect of the cow number on EI_D was found. However, there was a decreasing EI_D tendency with an increasing cow number (slope: -0.005), i.e., an increase in the cow numbers per farm from 30 to 60 results in an EI_D decrease of 10%.

Of total EI_D 30%±9% was for electricity consumption and rest (70%) from diesel or natural gas consumption. For this ration there was no significant difference between the dairies.

4.2.5 Feedstuff intake analysis

The feedstuffs consumed in these dairies were forage and concentrate feed, which were delivered separately. The forage was confined to alfalfa hay, fresh alfalfa, maize silage and straw. The energy intensities in the fresh and hay alfalfa were assumed to be the same. The concentrated feed consisted of barley, maize corn, wheat bran, oilseed meals (e.g., from soy beans, rapeseed, cottonseed and sunflowers), fat powder and complementary feeds in different ratios. Dairy farms were providing concentrates according to the advice of feeding experts; for lactating cows, the recommendation is 6.49 MJ NEL kg^{-1} DM (1.55 MCal kg^{-1}), and for bulls and other cattle, the recommendation is 10.67 MJ ME kg^{-1} DM (2.55 MCal kg^{-1}).

The q-value (NEL to ME ratio of feedstuff) in the farms was between 0.60 and 0.62, and the forage to concentrate ratio (based on DM) was between 1.08 and 2.73. The real ME intake (ME_r) in the dairies was more than the calculated standard ME requirements (ME_s). The ME_s was calculated for the lactation and maintenance of cows and the growth of other cattle in the dairies. These extra ME intakes refer to overfeeding and feed losses. The ME_r to ME_s ratio was between 1.08 and 1.35, with an average of 1.23±0.06.

A statistical analysis (table 30) of regions 1-3 showed significant q-value differences between the years, regions, their interactions and the number of cows in the dairies. The mean q-value for dairies in all 4 regions was 0.61±0.01. The region and the number of cows per farm had a significant effect on the forage to concentrate ratio. In region 1, it was 1.2±0.2, which differed from region 2 with 1.8±0.1 and region 3 with 1.9±0.1. For dairy 24, the forage-to-concentrate ratio was 1.60±0.01. A significant regression effect with a negative slope was observed between the forage to concentrate ratio and the cow number, revealing that the dairies with larger herds were using more concentrated feed than the smaller dairies. The ME_r to ME_s ratio was significantly different between all regions. The ME_r to ME_s ratio was 1.13±0.02 for region 1, 1.27±0.01 for region 2, 1.21±0.01 for region 3 and 1.20±0.05 for dairy 24 in region 4.

Table 30 Covariance analysis of the NEL to ME ratio (q-value), the forage to concentrate ratio and the real to standard ME intake ratio in the investigated dairy farms from regions 1-3.

	Analysed parameters									
Effect		NEL to ME ratio (q)			Forage/concentrate ratio			Real to standard ME intake		
	Num DF	Den DF	F Value	Pr > F	Den DF	F Value	Pr > F	Den DF	F Value	Pr > F
Year	2	38.8	5.28	0.0094	37.4	0.49	0.6167	40	0.30	0.7459
Region	2	19.7	4.22	0.0298	17.4	4.92	0.0202	18.5	16.93	<.0001
Year × Region	4	38.9	4.79	0.0031	37.7	0.65	0.6271	40.1	0.91	0.4698
Cow number	1	53.8	7.40	0.0088	35.1	11.96	0.0014	21.4	0.01	0.9275
ECM yield	1	56.6	1.17	0.2846	39.7	2.48	0.1229	21.9	3.44	0.0773

The energy input from feedstuff (EI_F) in the ECM production was between 4.15 and 6.16 MJ kg^{-1} ECM with an average of 4.77±0.45. The EI_F distribution is shown in figure 16.

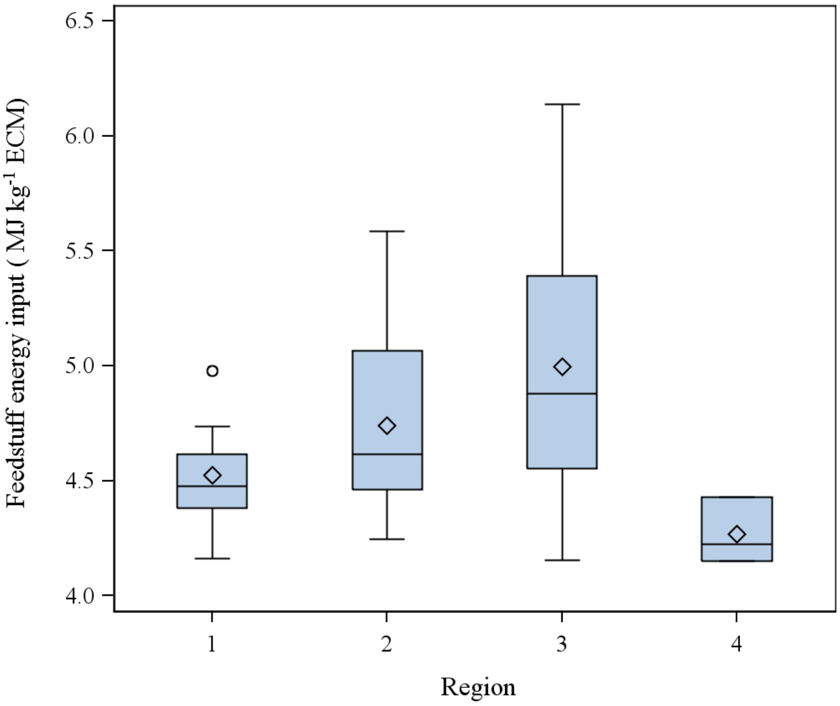


Figure 16 Feedstuff energy input in the ECM (MJ kg^{-1}) produced by regions 1-4.

A statistical analysis of the EI_F for regions 1-3 (table 31) showed a significant regression effect for the ECM yield on EI_F ($P<0.0003$), but no significant differences between regions 1-3, the years and the number of cows.

Table 31 Covariance analysis of feedstuff energy input in the ECM (MJ kg^{-1}).

	Tests of fixed effects for direct energy input			
Effect	Num DF	Den DF	F Value	Pr > F
Year	2	39.2	0.11	0.8942
Region	2	18.7	0.50	0.6135
Year × Region	4	39.5	0.46	0.7619
Cow number	1	31.1	0.18	0.6747
ECM yield	1	34.1	16.11	0.0003

The mean EI_F value for regions 1-3 was 4.76±0.20 MJ kg^{-1} ECM. For dairy 24, the mean EI_F value over the three years of investigation was 4.27±0.14 MJ kg^{-1} ECM. In the statistical model test (equation 18, p. 63) used to calculate the energy input from the feed intake, the estimated intercept was 6.39±0.38 MJ kg^{-1} ECM, and the estimated regression slope for the ECM yield was -0.00025±0.00006. This finding suggests that the feedstuff intake by a cow with a higher ECM yield was more efficient than that of a cow with a lower ECM yield (figure 17). For example, by increasing the ECM yield from 6,000 to 7,000 kg^{-1} cow^{-1} yr^{-1}, the EI_F is reduced by 5% from 4.89 MJ kg^{-1} ECM to 4.64 MJ kg^{-1} ECM.

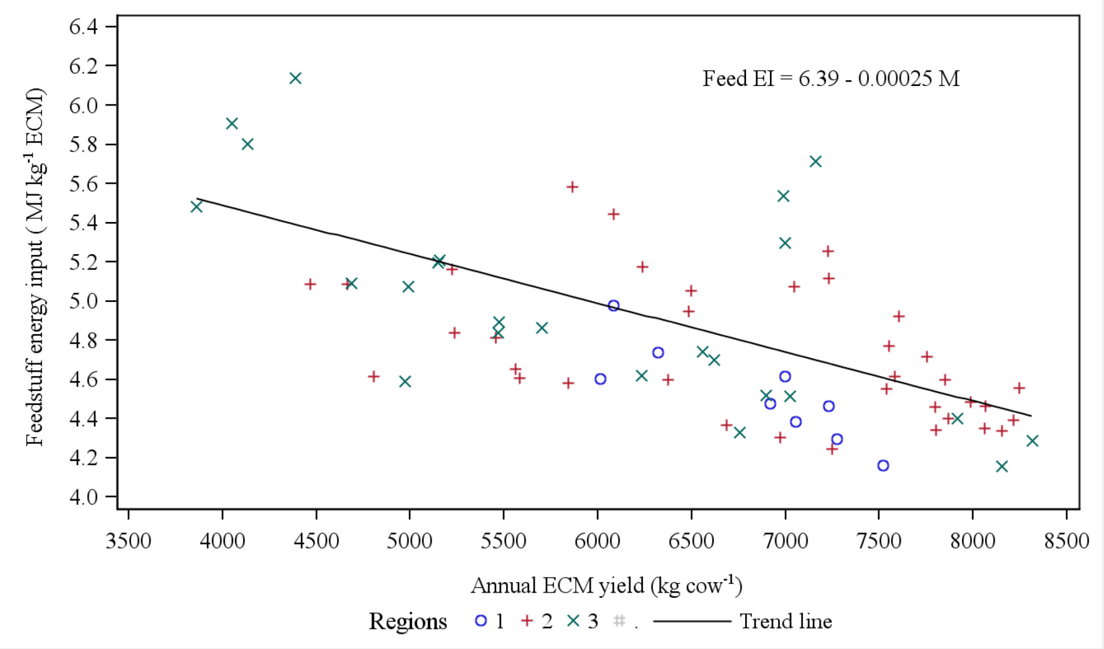


Figure 17 Scatter plot and estimated linear trend of the relationship between ECM yield (kg cow^{-1} yr^{-1}) and feedstuff energy input (MJ kg^{-1} ECM) for regions 1-3.

4.2.6 Heifer replacement analysis

The energy embodied in a heifer that replaced an old cow was calculated as the sum of the energy embodied in a calf (from birth) up to 150 kg, followed by a heifer up to 400 kg and finally reaching a mass between 500 and 550 kg within 24 months. The energy embodied in each stage was a different combination of the energy inputs from the buildings, machinery, direct energy sources and feedstuffs, which were allocated from the total consumption of all the dairies. The energy embodied in a heifer was between 20.1 and 35.2 GJ $head^{-1}$ in the investigated dairies with an average of 25.5±3.1 GJ $head^{-1}$ (see section 4.2.8).

The planned number of lactations per cow was an average of 6.01±1.09 years and was significantly different between regions, varying between 3.7 and 8 years. Region 1 averaged 4.7±0.05 years, which was different from region 3, with 6.8±0.3 years. No significant difference was observed between region 2, with 5.9±0.2 years, and regions 1 and 3. The planned number for region 4 was 5.0 years. During the investigation years, the heifer rearing rate (HRR) was different from the planned replacement rate. The real replacement rate was dependent on the prior replacement date, thereby establishing the date of the dairy, managerial and economic decisions for each year. Therefore, the HRR for the years of the study was calculated according to the number of cows sold and the decrease or increase in the cow number during each year as follows:

$$HRR = (CNEY + CNSY - CNBY) / MCN \qquad \text{Equation 27}$$

In which CNEY is the number of cows at the end of year, CNSY is the number of cows sold, CNBY is the number of cows at the beginning of year, and MCN is the mean cow number in a year.

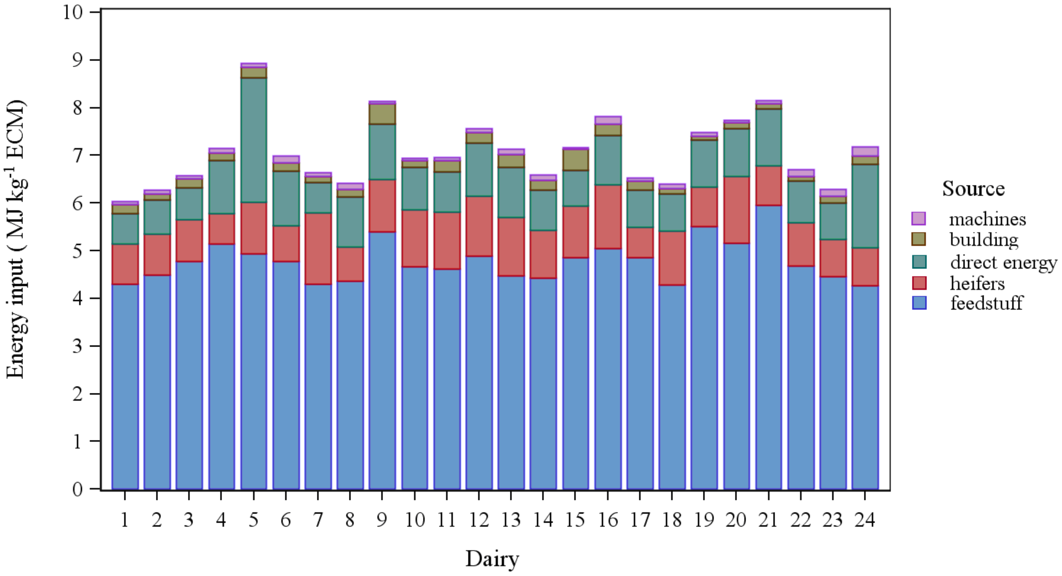
The HRR varied over the investigation years between 0 and 0.6, in which higher rates belonged to the dairies with a considerable change in the number of cows or those trying to improve the milk yield by replacing old cows with improved cow breeds. The average replacement rate for the dairies in regions 1-3 was 0.24±0.15 (i.e., approximately 4 lactations per cow) and for dairy 24 it was 0.20±0.05 (i.e., approximately 5 lactations per cow).

The energy input for heifer rearing (EI_H) was calculated according to the energy embodied in a heifer and the HRR in these dairies. The mean value of the EI_H was 1.09±0.40 MJ kg^{-1} ECM for regions 1-3 and 0.80±0.18 MJ kg^{-1} ECM for dairy 24 (region 4). The results showed that EI_H was not significantly affected by any of the factors in the statistical model (equation 18, p. 63).

4.2.7 Energy input in milk production

The energy input from the different sources of ECM production are presented in sections 4.2.3 to 4.2.6, and they represent the actual energy inputs for each cow per year divided by its annual ECM yield without considering the by-products (excrement and meat). The energy input for ECM ranged widely between 5.60 and 10.11, with an average of 7.07±0.82 MJ kg^{-1}. The highest ECM energy input belonged to dairy 5, which had the highest direct energy input, particularly in 2008 (section 4.2.4).

Figure 18 graphically presents the share of the energy input in ECMs from different sources for all the dairy farms (using a mean value for the years of investigation). As noted, the highest share belongs to the energy input from feedstuff, with a mean value of 67.5% of the total ECM energy input. The lowest share belongs to the energy input from machinery, with a mean of 1.3%, followed by the energy input from buildings, with a mean value of 2.7% of the energy input for milk production.



	Mean	*Min*	*Max*
Building	*2.7±1.0%*	*0.9%*	*6.1%*
Direct energy	*13.6±4.0%*	*9.2%*	*26.0%*
Feedstuff	*67.5±5.8%*	*54.4%*	*76.2%*
Heifer	*14.9±5.1%*	*4.7%*	*25.4%*
Machines	*1.3±0.6%*	*0.6%*	*2.6%*

Figure 18 Energy input from different sources in the ECM (MJ kg^{-1}) produced in dairies 1-24 (from an average of 3 years of investigation).

The statistical analysis of the ECM energy input for the investigated dairies using a model test (equation 18, p. 63) showed that the regional effect was significant (α=0.05). The regression effect of the annual ECM yield per cow was also significant for the energy input of the ECM (table 32).

Table 32 Covariance analysis of the energy input of milk (MJ kg^{-1} ECM) produced in the investigated dairies in regions 1-3.

	Energy input of ECM			
Effect	Num DF	Den DF	F Value	Pr > F
Year	2	39.6	0.53	0.9300
Region	2	18.1	5.45	0.0138
Year × Region	4	39.8	0.38	0.8191
Cow number	1	20.7	0.21	0.6184
ECM yield	1	21.1	23.52	<.0001

The solutions for this model are summarised in table 33 (see annex 2.3 for complete solutions). Both the ECM yield effect and the number of cows per farm on the EI_{ECM} are negative, i.e., the dairies with the higher number of cows and the higher ECM yield per cow had a lower milk energy intensity. For example, in region 3 which its estimated linear trend is between the other 2 regions, with an increase in the ECM yield from 6,000 to 7,000 kg cow^{-1} yr^{-1}, causing a 9% decrease in the energy input of 7.18 MJ kg^{-1} to 6.74 in region 3.

Table 33 Estimated solutions for the model test for the energy input in the milk (MJ kg^{-1} ECM) in the investigated dairies in the regions 1-3.[a]

		Solutions for Fixed Effects	
Effect		Estimate	Standard Error
Fixed effects (Intercept)			
Region	1	9.4587	0.6963
Region	2	10.3715	0.6118
Region	3	9.9088	0.5633
Regression effects			
Cow number (C)		-0.00274	0.005417
ECM yield (E)		-0.00044	0.000094

[a] Only the intercepts of significant or meaningful effects is given.

Table 34 shows the least squares means comparison between the investigation years and regions 1-3 for both methods. In this table, the means that had no significant differences from one another have the same letter. The EI_{ECM} in dairy 24 (region 4) was 7.18±0.23 MJ kg^{-1}.

Table 34 Least squares means of milk energy input (MJ kg^{-1} ECM) in regions 1-3.

		Least Squares Means	
Effect		Estimate*	Standard Error
Year	2008	6.8907 A	0.1563
Year	2009	6.8480 A	0.1562
Year	2010	6.9168 A	0.1559
Region	1	6.4018 a	0.2813
Region	2	7.3549 b	0.1367
Region	3	6.8987 ab	0.1709

* The difference between the estimates with the same letter was not significant.

4.2.8 Energy input for live cattle and meat production

The dairies kept the bulls and heifers until they reached an average of 415±161 kg body mass, when they were sold. The bulls were sold a few weeks after birth only in two of the dairies, and in some dairies, they were kept until reaching approximately 700 kg.

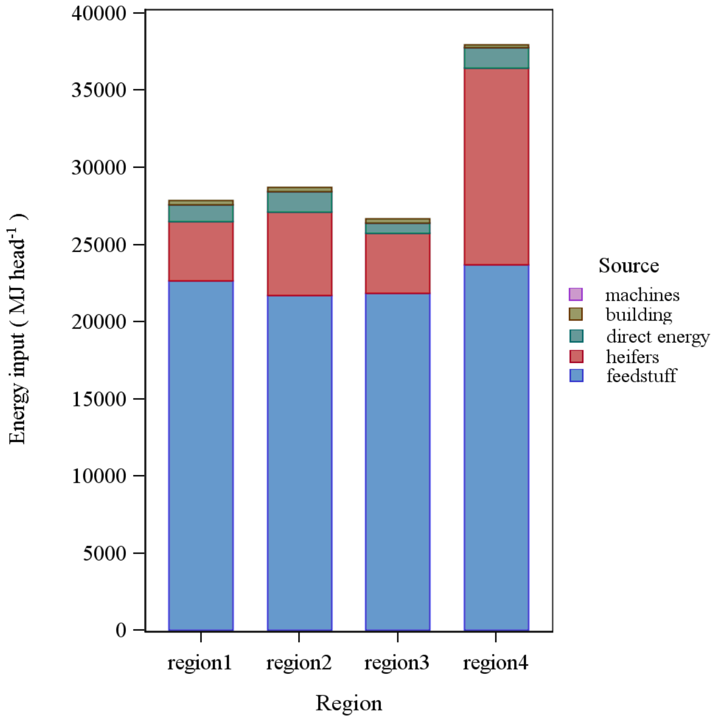
Energy input to live cattle (without considering the recycled energy from excrement) is the allocated energy input from the facilities, direct energy, and feedstuffs and the energy input from cattle in the prior category (table 35).

Table 35 Energy input for live cattle in the all dairies (GJ head^{-1})

		Energy input		
Cattle type	Mass (kg)	Mean	Min	Max
Calf	150	3.4±0.5	2.7	6.2
Heifer	400	16.0±1.9	13.1	22.5
	550	30.5±2.9	26.3	40.7
Bull	400	15.2±1.5	12.6	18.6
	700	36.1±3.4	30.1	44.1

The shares of different energy input sources from the total energy input in a heifer of 550 kg in the different regions are shown in figure 19. In this figure, the energy input from cattle in the prior categories (calf and heifer of 400 kg) is explained as the energy source share. The energy input from feedstuff was the main source of the energy input with a mean value of 80% in regions 1-3 and 62% in dairy 24 (region 4). The relatively high amount of energy input from direct energy sources in dairy 24 led to a higher energy input for a heifer in region 4.

In a bull of 400 kg, the share of the energy input was 78% from feedstuff, 17% from direct energy, 4% from buildings, and 1 % from machinery.



	Feedstuff	*Direct energy*	*Building*	*Machinery*
Region 1	*81%*	*14%*	*4%*	*1%*
Region 2	*75%*	*19%*	*5%*	*1%*
Region 3	*83%*	*14%*	*2%*	*1%*
Region 4	*62%*	*34%*	*3%*	*<1%*

Figure 19 Energy input from different energy sources in a heifer with 550 kg body mass in regions 1-4 (MJ head^{-1}).

4.2.9 Dairy energy efficiency indicators

4.2.9.1 Energy efficiency indicators in milk production

In section 4.2.7, the energy input in a cow was directly allocated to the milk yield without considering the excrement and meat produced by the cow. The energy input allocation to the dairy products and by-products was done according to the substitution method used for manure, and an allocation by caloric value was used for the milk and meat (section 3.3.7.2). According to figure 9 (p. 50), the energy output from excrement is recycled into the system by using it again as manure in the feedstuff production unit. This recycled energy constituted 15.4%±1.3 of the total energy input for a cow. Therefore, 82.5%±1.5 of the total ECM energy input was allocated to milk, 15.4%±1.3 to excrement and 2.1%±1.2 to meat. The energy intensity indicator in milk and meat production hereafter refers to the energy input allocated for each one.

The mean value for the energy intensity of milk was 5.84±0.69 MJ kg^{-1} for all regions, which belongs to the mean ECM yield of 6,525±1,221 kg cow^{-1} yr^{-1}. Figure 20 shows the energy intensity of milk for the investigated regions. The highest energy intensity belongs to dairy 5 in region 2, as discussed earlier, shown with extreme dot for region 2 in this figure.

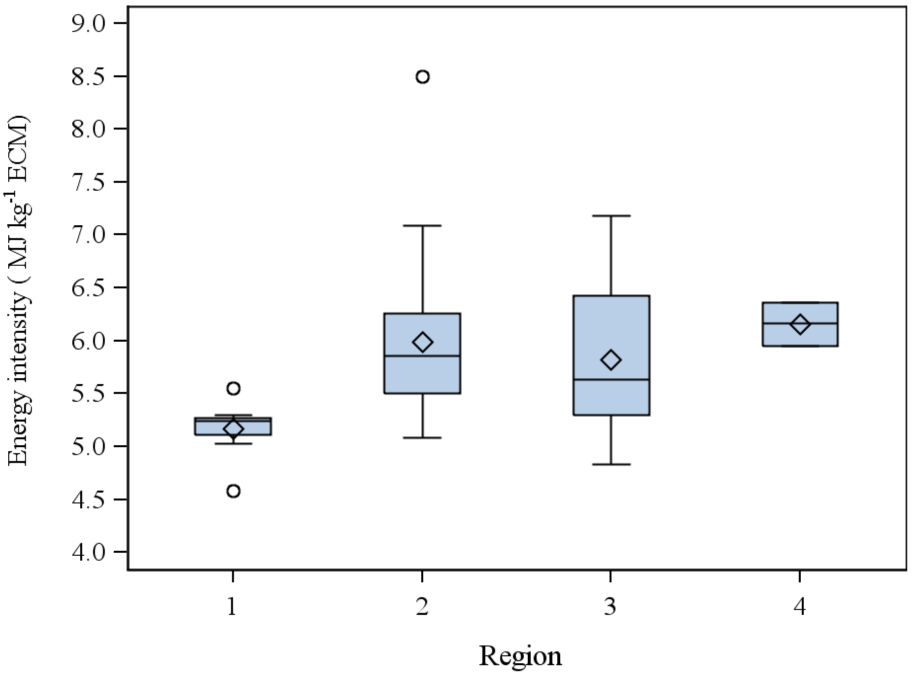


Figure 20 Box plot of the energy intensity in milk (MJ kg^{-1} ECM) from investigated regions (1-4).

The statistical analysis of the energy intensity in these farms is consistent with the results for unallocated energy input in milk as presented in table 32, in which only the significant effect of ECM yield was detected. Table 36 shows the estimated solutions for the model test for milk energy intensity in regions 1-3.

Table 36 Estimated solutions for the energy input model test for milk (MJ kg^{-1} ECM) in the investigated dairies in regions 1-3.[a]

		Solutions for Fixed Effects	
Effect		Estimate	Standard Error
Fixed effects (Intercept)			
Region	1	7.6676	0.6445
Region	2	8.4522	0.5735
Region	3	7.9828	0.5258
Regression effects			
Cow number (C)		-0.00067	0.005088
ECM yield (E)		-0.00036	0.000088

[a] Only the intercepts of significant or meaningful effects is given.

Figure 21 shows the regression trends between the ECM yield and the energy intensity in the investigated dairies. For example, for a farm in region 3 (the estimated linear trend of which is between the other 2 regions), an increase in the ECM yield of 6,000 to 7,000 kg cow^{-1} yr^{-1} causes a decrease in the energy input of 5.81 MJ kg^{-1} by 10% to 5.46. The impact of the cow number is very low and neglected.

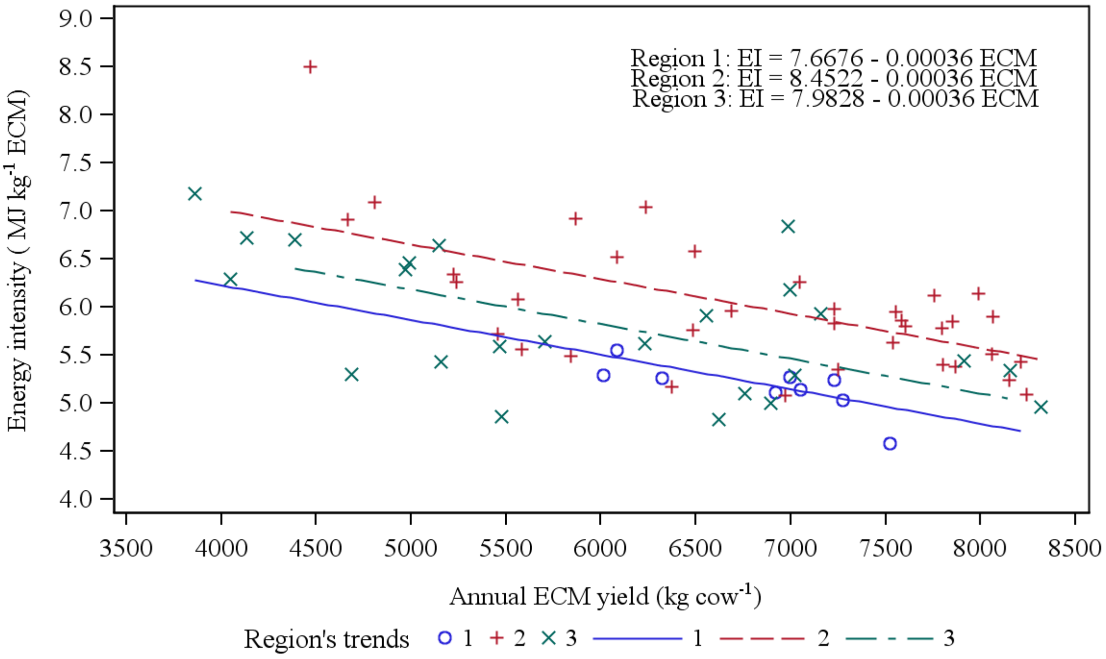


Figure 21 Scatter plot and estimated linear trends of the energy intensity in milk production (EI MJ kg^{-1} ECM) versus ECM yield (kg cow^{-1} $year^{-1}$) and for regions 1-3.

Table 37 shows the least squares means comparison between the investigation years and regions 1-3 for both methods. The EI_{ECM} in dairy 24 (region 4) was 6.16±0.20 MJ kg^{-1}.

Table 37 Least squares means of energy intensity in the ECM (MJ kg^{-1}) in the given investigation years and regions 1-3.

Effect		*Least Squares Means*	
		Estimate	Standard Error
Year	2008	5.6708 A	0.1386
Year	2009	5.6374 A	0.1386
Year	2010	5.6752 A	0.1383
Region	1	5.2673 a	0.2667
Region	2	6.0898 b	0.1298
Region	3	5.6264 ab	0.1621

* The difference between the estimates with the same letter was not significant.

In addition to the energy intensity (EI) indicator, the other indicators were also calculated for milk produced by the investigated farms under the EEV-based and the HHV-based scenarios according to section 2.6.2.6.1 (p. 33).

Energy efficiency indicators for ECM under the EEV-based scenario

After the energy intensity (EI), the energy output to input ratio (OIR), energy productivity (EP) and net energy yield (NEY) indicators were calculated for milk production. According to the EEV-based scenario (also called the CED-based scenario), for milk with an energy output of 3.15 MJ kg^{-1} ECM, the indicators were calculated and summarised in table 38. To avoid duplication, statistical analyses are neglected in this section because they were the same as the statistics calculated for EI (table 32). The regression effect is not mentioned here, and only the mean value of the indicators for the regions were summarised in table 38.

Table 38 Energy efficiency indicators in the ECM production in the investigated regions by the EEV-based scenario.

Region	*Efficiency Indicators*							
	EI (MJ kg^{-1} ECM)		OIR (MJ MJ^{-1} ECM)		EP (kg ECM MJ^{-1})		NEY (MJ kg^{-1})	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Region 1	5.27	0.27	0.60	0.02	0.19	0.00	- 2.12	0.27
Region 2	6.09	0.13	0.52	0.01	0.17	0.00	- 2.94	0.13
Region 3	5.62	0.16	0.56	0.01	0.18	0.00	- 2.47	0.16
Region 4	6.16	0.23	0.51	0.02	0.16	0.00	- 3.01	0.20
Average of all dairies	5.84	0.69	0.55	0.06	0.17	0.2	- 2.69	0.69

Energy efficiency indicators for ECM with an HHV-based scenario

The HHV energy efficiency data help in the investigation of dairy farm units independent of the feedstuff farm unit because the HHV of feedstuffs is nearly independent of the production process. Indicators were calculated by using the HHV-based scenario, but by replacing the EEV-based energy equivalent of the feedstuffs by their HHV equivalent. The indicators calculated using an HHV-based scenario were summarised in table 39. In comparing these two scenarios, it is clear that the energy intensity of milk as defined by the HHV-based scenario is approximately 4 times larger than that by the EEV-based scenario because the HHV feedstuff equivalents are, on average, higher than their EEV equivalents. In both scenarios, the OIR is less than 1, meaning the NEY has a negative value.

Table 39 Energy efficiency indicators in the ECM production following the HHV based scenario.

	Efficiency Indicators							
Region	EI (MJ kg^{-1} ECM)		OIR (MJ MJ^{-1} ECM)		EP (kg ECM MJ^{-1})		NEY (MJ kg^{-1})	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Region 1	20.52	0.86	0.15	0.00	0.05	0.00	- 17.37	0.86
Region 2	24.65	0.42	0.13	0.00	0.04	0.00	- 21.50	0.42
Region 3	23.91	0.52	0.13	0.00	0.04	0.00	- 20.76	0.52
Region 4	20.16	0.56	0.16	0.00	0.05	0.00	- 17.01	0.56
Average of all dairies	23.70	3.37	0.135	0.02	0.04	0.01	- 20.55	3.37

4.2.9.2 Energy efficiency indicators in meat production

The energy output from excrement produced by each cattle category was subtracted from the cattle energy input, and hereafter, the remaining energy input is called the energy embodied or intensity in live cattle or meat. The energy embodied in the live cattle from each category and per kg of boneless meat (40% of body mass) is summarised in table 40. In addition, the energy requirement for each 1 kg increase in body mass and meat from one category to the next category is shown in this table. When comparing this table and table 35 it is clear that the energy input value of cattle is 21% more than its energy embodied value, in reference to the re-circulated energy of excrement.

The energy demand for body mass increases with the increasing age of cattle. Thus, the lowest energy embodied for a one kg increase in meat belonged to growing calves with 63.7 MJ kg^{-1}, which ultimately reach 150 kg, and an embodied energy of 46.7 MJ kg^{-1} in meat. The highest embodied meat energy of 115 MJ kg^{-1} belonged to a heifer with 550 kg of body mass. Accordingly, the energy embodied in each kg of meat increases for a heifer with a body mass between 400 kg and 550 kg was the highest at 199.4 MJ kg^{-1} (79.8 MJ kg^{-1} body mass). The energy embodied in a heifer of 550 kg to replace an old cow was 25.5 GJ head^{-1}. The energy embodied per kg of meat increase for heifers between 150 and 400 kg was 104±14 MJ kg^{-1}, and it was 93±12 MJ kg^{-1} for bulls between 150 and 400 kg. The energy embodied per kilogram of meat produced by replacing an old cow (16±2 MJ kg^{-1} meat) was the allocated energy intensity (2.1% of total energy input for a cow) for the meat yield of a cow (4.2.9.1).

Table 40 Energy embodied in live cattle (MJ head^{-1}) and boneless meat (MJ kg^{-1}) produced from different cattle categories in the study dairies.

Cattle category/ Growing stage	*Factor*	*Unit*	*Mean*	*Standard deviation*	*Min*	*Max*
Birth → Calf	Meat [c]	MJ kg^{-1}	63.7	11.5	49.7	128.7
Calf (of 150 kg)[a]	Live	MJ head^{-1}	2,801.6	504.8	2,188.7	5,662.9
	Meat [c]	MJ kg^{-1}	46.7	3.4	36.5	94.4
Calf → Heifer 1 [b]	Meat [c]	MJ kg^{-1}	104.3	14.0	83.4	141.1
Heifer 1 (of 400 kg)	Live	MJ head^{-1}	13,227.4	1,854.4	10,532.0	19,773.4
	Meat [c]	MJ kg^{-1}	82.8	11.6	65.8	123.6
Heifer 1 → Heifer 2 [b]	Meat [c]	MJ kg^{-1}	199.4	23.3	159.9	256.6
Heifer 2 (of 550 kg)	Live	MJ head^{-1}	25,488.7	3,119.3	20,123.0	35,170.8
	Meat [c]	MJ kg^{-1}	115.0	14.7	91.5	159.9
Calf → Bull 1 [b]	Meat [c]	MJ kg^{-1}	93.3	11.5	75.3	120.8
Bull 1 (of 400 kg)	Live	MJ head^{-1}	12,058.5	1,459.0	9,719.6	15,409.4
	Meat [c]	MJ kg^{-1}	75.4	9.1	60.7	96.3
Bull 1 → Bull 2 [b]	Meat [c]	MJ kg^{-1}	140.0	14.6	115.6	178.9
Bull 2 (of 700 kg)	Live	MJ head^{-1}	29,072.6	3,202.1	23,748.3	36,873.9
	Meat [c]	MJ kg^{-1}	103.8	11.4	84.8	131.7
Cow [d]	Meat [c]	MJ kg^{-1}	16.3	1.9	12.8	23.7

[a] The energy input from milk feeding is not included.

[b] Growing stage from one cattle category to the next cattle category.

[c] The energy embodied in each kg of live body mass, the energy embodied in each kg of meat to be multiplied by 0.4.

[d] The energy value allocated to the meat produced by replacing old cows.

The statistical analysis for energy embodied in live cattle in the investigated dairy farms was performed for regions according to the reference model test (equation 18, p. 63). Only the significant and considerable results are discussed below.

The energy embodied in a live calf of 150 kg had a significant and direct relationship with the ECM yield of cows in regions 1-3. This result reveals that a calf from a cow with a higher ECM yield required higher energy for growth than a calf from a cow with lower milk yield. The estimated intercept and regression slope (significant in α=0.05) was 1,995±284 MJ head^{-1} and 0.11±0.05, respectively. In region 4, the embodied energy in a calf was 4,552±965 MJ head^{-1}.

The energy embodied in a heifer with 400 kg of mass (heifer 1) in the dairies with a higher ECM yield was higher than those in dairies with a lower cow ECM yield. The intercept for regions 1-3 was 9,716±284 MJ head^{-1}, and the regression slope of the ECM yield for cows was 0.45±0.22 (significant in α=0.05). The energy embodied in a heifer with a 550 kg body mass (heifer 2) was significantly different between the regions (α=0.05): 22,309±2,248 MJ head^{-1} in region 1, 25,941±1,091 MJ head^{-1} in region 2, 19,798±1,365 MJ head^{-1} in region 3 and 32,653±2,246 MJ head^{-1} in region 4.

The energy embodied in a bull of 400 kg (bull 1) was not affected by the region or cattle breed quality (ECM yield of cows). In regions 1-3, it was 12,058±1,459 MJ head^{-1}. The dairy 24 (region 4) had no bull on the farm. The energy embodied in a live bull of 700 kg (bull 2) in regions 1-3 was not different and had an average of 29,073±3,202 MJ head^{-1} or 104±11 MJ kg^{-1} meat.

Energy efficiency indicators for ECM under the EEV-based scenario

To calculate the energy efficiency indicators for meat production, the energy intensity in the meat produced by a bull of 400 kg was used because this cattle category was raised in most of the dairies for meat production. An energy output of 8.8 MJ kg^{-1} meat was used in the calculations. The calculated energy indicators for meat production in both scenarios (EEV and HHV based) are shown in table 41. No significant difference was found between regions 1-3, and no bulls were raised in dairy 24 (region 4).

Table 41 Energy efficiency indicators in meat production from a bull of 400 kg in regions 1-3 for both EEV- and HHV-based scenarios.

Efficiency Indicators							
EI (MJ kg^{-1})		OIR (MJ MJ^{-1})		EP (kg MJ^{-1})		NEY (MJ kg^{-1})	
Mean	SD	Mean	SD	Mean	SD	Mean	SD
EEV based							
75.4	9.12	0.12	0.01	0.013	0.000	- 66.57	9.12
HHV based							
313.8	24.75	0.03	0.00	0.003	0.000	- 305	24.75

Considering the indicators summarised in table 38 to table 41, the energy efficiency was higher for milk production than for meat production in these dairies. For milk production, the EP (EEV based) was 0.17 kg ECM per MJ energy input, and the OIR was 0.55 MJ MJ^{-1}. For meat production, the EP (EEV based) was 0.013 kg meat per MJ of energy input, and the OIR was 0.12 MJ MJ^{-1}. The energy input for meat production is 13.1 times more than that for milk production, and the HHV of meat is only 2.8 times that for milk production.

4.2.9.3 HHV conversion ratio for milk and meat production

Under the HHV-based scenario, it was assumed that the consumed feedstuff HHV was useful before it was converted to a dairy production HHV. To find a clear interpretation for energy conversion, the HHV-based OIR indicator was calculated again, only by considering the energy input from feedstuff consumption based on HHV. The new OIR was the HHV conversion ratio (HHV_{CR}). The HHV_{CR} is the ratio of HHV produced by a dairy (milk or meat) to the HHV from the feedstuff consumed for its production. The calculated HHV_{CR} for ECM was 0.136±0.018 MJ MJ^{-1}, and for meat, it was 0.033±0.023 MJ MJ^{-1}. The HHV_{CR} was slightly higher than the HHV-based OIR because the share of the energy sources other than feedstuff energy (HHV based) was small. A comparison of the HHV_{CR} for the meat and ECM reveals that by the consumption of one MJ feedstuff energy (based on HHV), 0.136 MJ of milk energy was produced in these dairies, which was 4 times more than the energy produced from meat production (0.033 MJ).

4.2.10 Sensitivity analysis of milk production

As shown in figure 18 (p. 89), the main sources of energy input for milk production were feedstuff (67.3%), direct energy (13.6%) and heifer rearing (14.9%). The main source of energy input in heifer rearing was also from feedstuff (79.7%), followed by direct energy (15.7%), for regions 1-3 (figure 19, p. 91). Therefore, feedstuff and direct energy were the main energy input sources in milk production. The sensitivity analysis for the milk EI indicator versus the uncertainty in feedstuff energy intensity was performed for feedstuff intake and direct energy consumption in the dairies. According to table 22 (p. 74), the sensitivity analysis for the EI of feedstuffs versus a 10% uncertainty in N fertiliser determined a mean sensitivity of EI of feedstuff of 3%. By assuming 10% uncertainty in the energy intensity of feedstuff and a simultaneous 10% uncertainty in feedstuff intake together with 14% uncertainty for the EI of milk, the result was calculated according to equation 19 (p. 64).

Table 42 summarises the sensitivity of the energy intensity in milk production. The analysis is based on an EI of 5.84 MJ kg^{-1} ECM as the average of all investigated farms (table 38, p. 94). Table 42 shows that the EI sensitivity of milk was highly dependent on the feedstuff intake. A 10% decrease or increase in the feedstuff intake (or energy intensity of the feedstuff) causes a 9.3% decrease or increase in the energy intensity of milk production.

Table 42 Sensitivity of the average energy intensity for ECM production in regions 1-4 (5.84±0.69 MJ kg^{-1}).

Uncertainty source	*Uncertainty (%)*	*Sensitivity of energy intensity of ECM (%)*
Energy intensity of feedstuffs	3 [a]	2.7
Feedstuff intake in the dairies	10 [b]	9.0
Feedstuff intake in the dairies	14 [c]	13.2
Feedstuff intake in the dairies	20	18.8
Direct energy consumption in the dairies	10	2.0
Direct energy consumption in the dairies	20	4.0

[a] Resulting from 10% uncertainty in N fertiliser consumption (or diesel consumption) for feedstuff production;

[b] Or 10% uncertainty in the energy intensity of feedstuff;

[c] Or 10% uncertainty in feedstuff intake and a simultaneous 10% uncertainty in the energy intensity of feedstuff

5 Discussion

5.1 Energy efficiency in feedstuff production

The most effective feedstuffs in relation to the DM and energy yields as well as to the total energy efficiency indicators are spring maize silage and alfalfa. The high amounts of DM yield from both crops and the low N fertiliser input in alfalfa has caused a relatively low energy intensity in maize silage and alfalfa. In this study, the EI was calculated for spring maize silage at 2.45 and that of alfalfa was at 2.92 MJ kg^{-1} DM. For summer maize silage, the result was considerably higher at 4.45 MJ kg^{-1} DM. Rapeseed had the highest EI, with 12.36 MJ kg^{-1} DM as a result of a higher N fertiliser input and irrigation, as well as a lower DM yield (2,550 kg ha^{-1}), followed by maize corn (9.19 MJ kg^{-1} DM) and barley (6.8 MJ kg^{-1} DM).

The EI for feedstuff production, found in the literature (table 14, p. 44) and the calculations herein (table 20, p. 73), varies relative widely. The estimated value for the EI of maize silage (2.24 to 2.49 MJ kg^{-1} DM) by Kraatz (2009) is similar to the value for maize silage calculated in this study. The EI of alfalfa calculated by Tsatsarelis & Koundouras (1994) is 2.53 MJ kg^{-1} DM and is close to the calculated in this study and by Refsgaard et al. (1998) at 2.98 MJ kg^{-1} DM. The EI used for alfalfa by Frorip et al. (2012), 1.59 MJ kg^{-1} DM, is half this value. They used the value according to FAO data, without giving further details.

For cereals, the resulting EI in this study and other studies in Iran are quite different than those of European countries. The EI of maize corn estimated in this study (9.19 MJ kg^{-1} DM) is higher than the one calculated by Lorzadeh et al. (2012) for Iran at 6.58, and the one used by Frorip et al. (2012) in Estonia at 5.13 MJ kg^{-1} DM. The lower estimated EI by Lorzadeh et al. (2012) refers to a lower N fertiliser input than that in this study and to use of a different amount of primary energy for the supply of electricity (3.6 MJ kWh^{-1}), for mechanised irrigation systems. Similarly, the allocated EI for barley grain in this study (6.76 MJ kg^{-1} DM) is approximately 3 times more than the 1.9-2.3 MJ kg^{-1} DM estimated by Kraatz (2009) for Germany but similar to the one estimated by Ghasemi Mobtaker (2010) in Iran. For wheat grain, the calculated EI in this study (4.35 MJ kg^{-1} DM) is nearly 2 times more than that reported by Frorip (2012) and Kraatz (2009). Oilseed meals are among the main feedstuffs consumed in dairy farms. The calculated EI for rapeseed in this study is 12.36 MJ kg^{-1} DM (allocated EI to rapeseed meal 9.25 MJ kg^{-1} DM), or much more than that estimated by Kraatz (2009) at 5.15 MJ kg^{-1} DM, and even more than another report from Iran with 9.1-10.7 MJ kg^{-1} DM (Mousavi-Avval et al., 2011) but for 25% lower yield (1,912 kg ha^{-1} DM).

The reason of such differences in the EI of crops, especially for cereals and oilseeds, are high differences in the amount of N fertilisers input and fuel consumption during the machinery operations as well as the high consumption of irrigation water in the conventional border-check system. The energy input from these sources in calculations of this study is approximately 2-3 times of that of Refsgaard et al (1998, for wheat with yield of 3-4 t ha^{-1} and 50% less than that in this study).

5.2 Energy intensity in milk production

The mean milk yield of the regions in the investigated dairy farms ranged between 5,901±584 kg ECM cow^{-1} year^{-1} in region 3 and 6,813±398 kg ECM cow^{-1} year^{-1} in region 2, farm 24 (region 4) had a mean yield of 8,073±67 kg ECM cow^{-1} year^{-1}. The milk yield was driven by the feed intake. The increase in milk yield through the increase in feed intake was as high that causing to decrease in the EI. In this way, the EI was decreasing along with higher milk yields. The EI, calculated only with the energy input from feedstuff, was 4.85 MJ kg^{-1} ECM in region 3, 4.80 MJ kg^{-1} ECM in region 2 and 4.27 MJ kg^{-1} ECM in dairy farm 24 (region 4), figure 16. Kraatz (2009) calculated that this effect is diminishing with milk yields higher than 8,000 kg ECM cow^{-1} year^{-1}.

The energy input for milk production consists of the energy input from feedstuffs, heifer rearing, direct energy, buildings and machinery. The share of each of these energy input sources for the total milk energy input varies and depends on several factors analysed by statistical models, namely the location of the dairy farm (region), year, number of cows in the farm, milk yield of the cows and the interactions of these factors. The EI was calculated using the total primary energy input in milk production for all investigated dairy farms (with a milk yield of 6,585±1,221 kg ECM cow^{-1} yr^{-1}), and it ranged between 4.58 and 8.50 MJ kg^{-1} ECM, with a mean value of 5.84±0.69 MJ kg^{-1}. This result assumed a manure energy output of 0.33 MJ kg^{-1} (substitution method, section 3.3.6.2). Without this allocation of energy input to manure as a by-product of dairy cattle, the EI would be approximately 1 MJ kg^{-1} ECM higher. In any case, the EI calculated with the total primary energy input is decreasing with increasing milk yield, as it is with EI, which was calculated only with the energy input from feedstuff (table 31, figure 17), described in above paragraph. With an increase of 1,000 kg ECM cow^{-1} year^{-1}, the total EI decreases by 0.36 MJ kg^{-1} ECM, giving a decrease of 6.2% of the mean EI.

In most of the previous studies, excrement were neglected as energy outputs, and thus, the milk production energy input was allocated between milk and meat, but these studies included pasture in the keeping systems. The EI calculated in these studies ranged between 2.2 MJ kg^{-1} ECM for an organic system in Denmark (Refsgaard et al., 1998) and 5.0 MJ kg^{-1} milk for a conventional system in Netherland (Thomassen et al., 2008; cp. table 15, p. 46). The milk type and yield reported in these studies varied from 1.5% to 4.4% fat content in milk and a milk yield from 5,521 to 8,000 kg cow^{-1} year^{-1}. The mean EI, which was calculated in current study using an allocation of all energy inputs only to milk, with 7.08±0.82 MJ kg^{-1} as well as with the allocation of all energy inputs to milk, meat and manure, with 5.84±0.69 MJ kg^{-1} ECM, being higher than these figures from other studies. The EIs reported by Thomassen et al. (2008; 5.0 MJ kg^{-1} milk) and Frorip et al. (2012; 5.3 MJ kg^{-1} milk) were very close to the results given here. With the employed FAO data for EI of feedstuffs by Frorip et al. (2012) the investigated EI for milk production in Estonia is similar to EI in this study. Even if the mean milk yield of the investigated farms is in the lower range of that of the other studies, the high EI in feedstuff production is the main reason for the higher EI in milk production.

Different procedures were used for the allocation of energy input to milk and its by-products. Refsgaard et al. (1998) converted the meat yield to milk yield by using their caloric values (HHV), i.e. he allocated 96.5% to the milk and 3.5% to the meat. Cederberg & Stadig (2003) allocated energy to milk and meat by using economical factors (92% of the total energy input for milk), biological factors (85%) and system expansion to beef production (87%). Grönroos et al. (2006) used a proportion of 87% for milk and 13% for meat according to a variant of Cederberg & Stadig (2003; for a rearing rate of 37% in Sweden). Kraatz (2009) allocated 59% of the energy input to milk, 18% to meat, 2% to calves and 21% to excrement, by using a system expansion for manure and the biological and physiological relations between meat and milk. With these different allocation procedures, the EI in milk production ranged between 2.2 and 5.0 MJ kg^{-1} milk in these other studies (cp. table 15, p. 46). In this study 83% of the total energy input was allocated to milk, 15% to excrement and 2% to meat. The energy allocated to manure was by using of the substitution method (0.33 MJ kg^{-1} fresh manure) and between milk and meat according to the HHV relationship (section 3.3.6.2 p. 55).

5.3 Energy input from different sources

Figure 18 and accordingly figure 22 illustrate the share of different energy input sources for milk production. Considering that approximately 73% of the energy input in heifer rearing is from feedstuff (in regions 1-3), the energy input from feedstuff for cows and heifers has a share of approximately 79% of the total energy input to milk production. Direct energy, with its 14% share of the total energy input, is the other source worthy of mention. All other energy input sources play only a marginal role, with a share of less than 3% of the total energy input. Kraatz (2009) calculated a share of feedstuff energy input of approximately 50% (1.76 MJ kg^{-1} ECM) of the total energy input in milk production. For heifer rearing, she calculated 20% (0.70 MJ kg^{-1} ECM), and for machinery, milking and other technical facilities together, she designated 27% (0.97 MJ kg^{-1} ECM) of the total energy input. Furthermore, Kraatz

(2009) could show the influence of the replacement rate (service life of a dairy cow) on EI. She calculated nearly the same EI for a milk yield of 7,000 kg ECM cow^{-1} year^{-1} and a related replacement rate of 20% (5-year service life of the dairy cow) as for a milk yield of 8,000 kg ECM cow^{-1} year^{-1} and a related replacement rate of 30% (3.3 years of service life for the dairy cow). The energy input from heifer replacement was neglected by Bockisch and Ahlgrimm (2000), Frorip et al. (2012), Grönroos et al. (2006) and Refsgaard et al. (1998). However, the results of this study as well as the studies by Kraatz (2009) show that heifer rearing makes up a relatively high share of the energy input, has the potential to improve EI (especially with a longer service life for dairy cows) and should be considered in energy analyses.

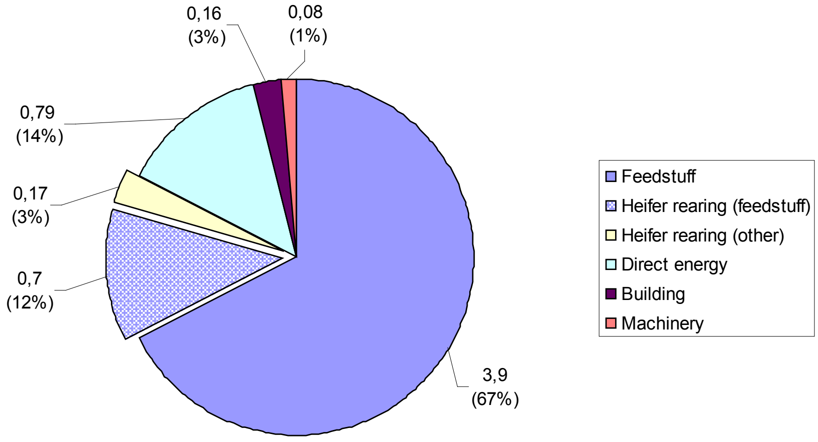


Figure 22 Average energy input share of different sources from total energy embodied in the ECM (MJ kg^{-1}) produced in the investigated dairy farms.

The EI of milk production can be notably improved within the sphere of feedstuff, both for dairy cows and for heifer rearing. Improving the EI in feed production has been revealed as the most substantial way to improve the EI of milk production. This is derived from the high share of energy input in feedstuff of about 79% of the total energy input in milk production (inclusive heifer rearing) and the high sensitivity of the total energy input to the energy input in feedstuff production. A more extensive use of maize silage and alfalfa in dairy cattle feeding would decrease the energy intensity in milk production.

In the investigated farms, the feedstuff intake was on average of 23% more than the estimated requirements according to current knowledge of animal nutrition (Kirchgeßner et al., 2008). It is believed that storage and feeding losses led to this high value for feedstuff intake. Another source of excessive feedstuff intake is observed in cattle overfeeding. A feed supply designed according to the known animal nutritional requirements and a careful handling of feedstuff is a basic measure for improving the EI. Kraatz (2009) found out that pasture and grazing possibilities in farms causes lower energy input from feedstuff source, as a result of the elimination of energy input from harvesting and transportation. Kraatz (2009) calculated an EI of 4.03 MJ kg^{-1} ECM if the cattle kept without pasture. With half day pasture the EI was decreasing to 3.54 MJ kg^{-1} ECM (by 12%).

Other potential to decrease the EI for milk is reducing the direct energy consumption in farms. The share of the direct energy input in dairy farms in this study (14%), is close to that of Refsgaard et al. (1998, 20%), and Thomassen et al. (2008, 10%). But the absolute value for direct energy input (0.82 MJ kg^{-1} ECM) is higher than others (Refsgaard et al. (1998): 0.7 MJ kg^{-1} ECM, and Thomassen et al. (2008): 0.5 MJ kg^{-1} ECM). The diesel or natural gas consumption at 70% was the main source of the direct energy input for heating, cleaning and the generation of electricity. It reveals that these are good potentials to save energy. Especially electricity generation (reported in dairy 5) was energy consuming because of low efficiency.

Within the investigated range of milk yield (3,861- 8,317 kg ECM cow^{-1} $year^{-1}$) and herd size (9-104 cows per farm) the EI was decreasing with the increasing milk yield and the increasing herd size. So at least within these ranges, it seems that a solution to decrease the EI is an increase in ECM yield and also herd size. To identify trends in the behaviours of large dairy farms, it is necessary to have more large dairy farms to investigate.

5.4 Energy input in meat

The EI for meat is strongly dependent on the cattle category. According to table 40 (p., 96), the embodied energy in boneless meat from cattle kept for meat production purpose is 46.7 MJ kg^{-1} for a calf of 150 kg, 75.4 MJ kg^{-1} for a bull of 400 kg and 103.8 MJ kg^{-1} for a bull of 700 kg. The bulls in this study were mostly sold in the 400 kg category. The allocated energy from a dairy cattle system to meat produced from slaughtered cows is 16.3 MJ kg^{-1}. The large difference between the allocated energy intensity and the one calculated for bulls may complicate the allocation method, considering the caloric values, but also the quality of these meats are quite different.

The EI of meat production from other studies is different. The reported value according to the GEMIS data bank for beef meat in Germany is 56.4 MJ kg^{-1} meat (Taylor, 2000). Williams et al. (2006) reported a 28 MJ kg^{-1} carcass, i.e., 35 MJ kg^{-1} of boneless meat for conventional beef production in the UK. Frorip et al. (2012) calculated the energy intensity of meat at 69 MJ kg^{-1}. These differences are again due to the differences in keeping systems, but are especially due to the energy intensity of feedstuff.

5.5 Scenarios for the determination and conversion of energy equivalents of biomass in crop production and dairy farming

According to the possible investigation scenarios to determine and to convert the energy equivalents for biomass described in section 2.6.2.6.1 (p. 33), milk production is a tangible example for comparing the advantages and disadvantages of the different scenarios in a system investigation.

According to scenario A, the energy equivalent of biomass is equal to its EEV. Scenario B differs from scenario A by using of the HHV-based energy equivalent instead of the EEV-based energy equivalent for biomass. Scenario C and D are a broadening of scenario A and B in such a way that the outputs are converted to an energy value (for HHV base). In scenario C for biomass input the EEV and for biomass output the HHV is used as the energy equivalent. In scenario D for both input and output, the HHV of biomass is used as the energy equivalent. The advantage of the utilisation of scenarios A and C is the possibility to investigate both units (feedstuff and milk production) together, for different dairy farm systems and at different locations. In scenarios B and D the efficiency of the feedstuff unit has no impact on the efficiency of the dairy unit. In other words, different feed production systems have no effect on the investigation of dairy farm systems because instead of the EEV-based energy equivalent, the HHV-based energy equivalent of feedstuff is used, which is an inherent specification nearly independent of the production process. The advantage of using scenarios B and D in dairy farming systems (for HHV base) is the ability that it gives us to compare only the dairy units.

The calculated EI for feedstuffs, milk and meat was actually carried out according to scenario A. The EI calculated with scenario B in this study is 23.7 and 314 MJ kg^{-1} for milk and meat, respectively. Frorip et al. (2012) calculated an EI of 20 and 255 MJ kg^{-1} respectively for milk and meat by use of scenario C. These values are respectively 16% and 19% less than those calculated in this study. While, the EI calculated by Frorip et al. (2012) by scenario A (5.31 MJ kg^{-1} milk), is 9% less than that calculated in this study (5.84 MJ kg^{-1} ECM).

Scenario C was also used to calculate the OIR and NEY indicators in the feedstuff farm unit as well as the dairy farm unit. According to the results of this study, the EEV-based OIR indicator for the analysis of milk production (scenario C) is 0.55 MJ MJ^{-1} and for meat (beef) is 0.12 MJ MJ^{-1}. These results indicate that for each MJ consumed primary energy is gained only 0.55 MJ caloric value (HHV) from ECM and 0.12 MJ from meat. These OIR are less than 1, while in investigated crops in this study it is at least 2 (maize corn and barley grain). The HHV-based OIR indicator (Scenario D) calculated for ECM is 0.135 MJ MJ^{-1} and for meat is 0.030 MJ MJ^{-1}. In scenario D, energy input per each MJ caloric value from meat is approximately 4.5 times more than that for ECM.

The HHV conversion ratio is calculated in this study by excluding the energy input sources other than the feedstuffs in calculation of OIR by scenario D. It compares the consumed and produced HHV in the process. The HHV conversion ratio was 0.136 MJ MJ^{-1} in ECM production and 0.033 MJ MJ^{-1} in meat (beef) production. The results of this indicator are nearly same as the OIR indicator, because the share of feedstuff energy is much higher than the excluded energies, but HHV conversion ratio could better demonstrate this concept. In reverse form, this ratio means that for 1 MJ caloric value of ECM yield approximately 7.35 MJ from consumed feedstuffs is needed. For 1 MJ caloric value of meat, 30.3 MJ of feedstuffs is needed.

6 Conclusions

The demand for dairy products in Iran is growing. Dairy cattle farming in Iran is carried out intensively in dairy farms usually without pasture and grazing possibility, especially in north-western Iran. The feedstuffs for dairy farms are produced intensively in crop farms in competition with food crops. In 2006, 85% of the dairy cattle population in Iran were kept in herds consisting of 50 or fewer head. However, herd size and intensification are growing in the course of the further development of the dairy farms.

For the investigations of the energy efficiency in milk production the dairy farming system was divided into two sub-systems: the feedstuff production unit and the dairy farm unit. The outputs of the first unit were handled as the inputs of the second unit. Data were gained by a questionnaire from a feedstuff producing company and 24 dairy farms in north-western Iran.

The energy intensity (EI) in feedstuff production (in MJ kg^{-1} DM) was 2.92 for alfalfa, 6.76 for barley grain, 9.19 for maize corn, 12.36 for rapeseed, 2.45 for spring maize silage, 4.45 for summer maize silage and 4.35 for wheat grain. From these feedstuff crops, the best one for all efficiency indicators and all three energy bases (HHV, MEV, and NEL) was spring maize silage followed by alfalfa and wheat. The allocation of the energy input between products and by-products was done according to the ratios of their MEV. In feedstuff production the main sources of energy input were N fertiliser, fuel and irrigation (conventional border-check irrigation) with a share of about 32%, 28% and 20%, respectively. Thus, savings in these three fields, including N fertiliser production, would have a large effect on improving energy efficiency. According to the sensitivity analysis, 10% reduction in each one of these sources (at the same yield) could causes on average 2-4% reduction in the energy intensity.

For milk production a mean EI of 5.84±0.69 MJ kg^{-1} ECM was calculated for the investigated farms with a mean milk yield of 6,585±1,221 kg cow^{-1} yr^{-1}. The main source of energy input in milk production was feedstuff with approximately 79% of the total energy input (67% directly in dairy and 12% in heifer feeding). With about 14% of the total energy input, direct energy consumption was the only further considerable source of energy input. The sensitivity analysis confirmed that these sources of energy input had a strong influence on energy efficiency. Thus, additionally to the mentioned potential savings in feedstuff production, the energy efficiency could be improved by the reduction of direct energy input for heating and cleaning (70% of direct energy input) as well as the on farm generation of electricity, and most notably by savings in feedstuffs. Feedstuff savings could be achieved by reducing feed losses (beginning from harvesting, beyond storage up to cattle feeding), the calculation and administration of the feed rations according to cattle requirements (known from animal nutrition) and the use of energy efficient feedstuff (e.g. spring maize silage and alfalfa). Within the range of the milk yield found in the investigated farms (3,860-8,320 kg ECM cow^{-1} yr^{-1}), EI was decreasing with increasing milk yield. According to the mixed linear model used for statistical analysis, the EI was decreasing by 0.36 MJ kg^{-1} ECM when the milk yield was increasing by 1,000 kg ECM cow^{-1} yr^{-1}. Thus, within this range the increase of milk yield could improve energy efficiency, especially in the lower range.

The allocation of the energy input to manure, done on the basis of the substitution of mineral fertilisers, resulted in a share of 15% of the total energy input and turned out to be an appropriate solution. The allocation of the remained energy input between milk and meat, done on the basis of their HHV, resulted in a share of 83% and 2% of total energy input, respectively. This reveals that in case of a long service life of dairy cattle (> 4 years) the allocation to meat could be neglected.

Beside milk production, cattle were kept in the farms for meat production purposes. The calculated EI in boneless meat produced by bulls up to 400 kg body mass was 75.4 MJ kg^{-1} and produced by bulls up to 700 kg body mass was 103.8 MJ kg^{-1}. The allocated EI of the replaced slaughtered dairy cows was 16.3 MJ kg^{-1} meat. On the one hand, this big difference emphasises that the meat from dairy cows is a by-product only. On the other hand, it denotes that a higher EI could be valued to the meat of replaced slaughtered dairy cows although considering the different meat quality.

EI in milk production calculated on the basis of the higher heating value (HHV) of feedstuffs as energy equivalent instead of the energy embodied in their production (EEV) was 23.7±3.37 MJ kg^{-1} ECM and 314±25 MJ kg^{-1} boneless bull meat (400 kg body mass).

Energy output input ratio (OIR) based on the HHV ranged between 2.03 MJ MJ^{-1} for maize corn and 7.75 MJ MJ^{-1} for spring maize silage production. While, in milk production OIR was 0.55 MJ MJ^{-1} and in meat production 0.12 MJ MJ^{-1}. This emphasises that energy efficiency in livestock farming is on average on order of magnitude lower than in crop production.

The calculated EI for dairy farms and the related feedstuff production in this study was higher than those of most other studies. The predominant reasons were the higher EI in feedstuff production and higher consumption of feedstuffs in dairy farms than requirements.

More researches should be done to gather a wider data base for different types of dairy farming in different regions with different feedstuff. This would allow a better comparison between the different types and the deduction of target values so that energy efficiency of production processes can be better evaluated than so far. This would also enable further development of assessment methods. The assessment of energy efficiency should be complemented by further indicators characterising further ecological aspects as well as economic and social aspects.

Summary

There is an increasing demand for products from cattle farming, especially dairy products, driven by growing population and increasing living standards. The global production of dairy goods in 2050 is projected to be doubled since 1999. To catch this goal dairy farming is increasing and becoming more intensive and therefore, it is attendant on higher energy inputs, also in Iran. Energy efficiency of livestock production is lower than that of crop production. Intensive farming is seriously challenged by environmental problems, the depletion of fuel resources and increasing energy prices. Energy efficiency improvement is one of the most important challenges.

The aim of this study was to estimate and assess the energy efficiency of dairy cattle farming and the related feedstuff production in common systems that are prevalent in north-western Iran. Feedstuff production farms and dairy farms in Iran usually were completely separate. Data were gained from a company producing feedstuff in Moghan plain, in north-western Iran, and from 24 dairy farms, also located in north-western Iran, with different herd sizes and milk yields. For this, a questionnaire was elaborated and data were gathered for a period of three years. A method of investigation was devised on the basis of the cumulative energy demand (CED) method introduced by VDI guideline 4600 and ISO standard 14044, which is used in life cycle assessment (LCA). These methods enabled to analyse the energy efficiency of feedstuff production and milk production separately, and to compare several farms, that differ in herd size, milk yield, feedstuff, keeping systems and management. Energy efficiency was characterised by several indicators, the most important are the energy intensity (EI) and energy output input ratio (OIR). A sensitivity analysis described the uncertainties of the results and identified connotative fields for further investigations.

The EI in the investigated feedstuff production (in MJ kg^{-1} DM) was 2.92 for alfalfa, 6.76 for barley grain, 9.19 for maize corn, 12.36 for rapeseed, 2.45 for spring maize silage, 4.45 for summer maize silage and 4.35 for wheat grain. Spring maize silage was the most advantageous feedstuff out of all the investigated crops for all the efficiency indicators, followed by alfalfa and wheat. N fertiliser, fuel consumption and irrigation were the main sources of energy input in feedstuff production, with a share of approximately 32%, 28% and 20%, respectively. The energy input was allocated to main and by-product feedstuffs according to the ratio of their metabolisable energy value (MEV).

The mean EI of the produced energy corrected milk (ECM) was 5.84±0.69 MJ kg^{-1}, calculated for the investigated farms with a mean milk yield of 6,585±1,221 kg cow^{-1} yr^{-1}. Feedstuff was the main source of the energy input in milk production, with approximately 79% of the total energy input (67% directly in dairy feeding and 12% in heifer feeding). Heifer rearing (rearing rate 0.25) had a share of 15% (inclusive feeding), and direct energy of 14% of the energy input in milk production. Direct energy input consisted of 70% of diesel and natural gas consumption for heating and cleaning and of 30% electricity for machinery and lighting. Buildings and machinery had a share of 3% and 1% of the energy input in milk production, respectively. The sensitivity analysis confirmed that the energy input from feedstuff had the strongest influence on the energy efficiency in milk production. The EI was decreasing with an increasing milk yield (-0.36 MJ kg^{-1} ECM per +1,000 kg ECM cow^{-1} yr^{-1}), within the range of the milk yield found in the investigated farms (3,860-8,320 kg ECM cow^{-1} yr^{-1}). The energy input was allocated to manure on the basis of the substitution of mineral fertilisers and resulted in a correspondent share of 15% of the total energy input. The allocation of the remained energy input between milk and meat was done on the basis of their HHV and resulted in a share of 83% and 2% of the total energy input, respectively.

In the investigated dairy farms beside milk production, meat was produced with the remaining calves and further cattle. The EI in boneless meat produced by bulls up to 400 kg body mass was 75.4±9.1 MJ kg^{-1} and produced by bulls up to 700 kg body mass 103.8±11.4 MJ kg^{-1}. Whereas, the allocated EI for meat of the replaced slaughtered dairy cows was 16.3 MJ kg^{-1} meat.

By calculating the milk production EI on the basis of the higher heating value (HHV) of feedstuffs, as their energy equivalent instead of the energy embodied in their production (EEV), it yielded in a mean EI of 23.7±3.37 MJ kg^{-1} ECM and an EI of 314±25 MJ kg^{-1} bull meat (400 kg body mass).

The HHV-based energy output input ratio (OIR) ranged between 2.03 MJ MJ^{-1} for maize corn and 7.75 MJ MJ^{-1} for spring maize silage production. While, in milk production OIR was 0.55 MJ MJ^{-1} and in meat production 0.12 MJ MJ^{-1}. This emphasises that energy efficiency in livestock farming is lower than that in crop production.

In literature, lower or as well as similar results were found for the EI in milk production. More researches should be done to gather a wider data base and to enable the deduction of target values so that production processes can be better assessed than so far.

Zusammenfassung

Mit der wachsenden Weltbevölkerung und höheren Lebensstandards steigt die Nachfrage an Produkten aus der Rinderhaltung, insbesondere aus der Milchviehhaltung. Im Jahr 2050 wird sich die globale Erzeugung von Milchprodukten gegenüber 1999 verdoppelt haben. Auf diesem Weg nehmen Umfang und Intensität der Milchviehhaltung immer weiter zu. Diese Entwicklung geht einher mit immer höheren Energie-Inputs, dies gilt auch für den Iran. Die Energieeffizienz der Tierproduktion ist geringer als die der Pflanzenproduktion. Die intensive Landwirtschaft ist durch Umweltprobleme, die Erschöpfung von Kraftstoffressourcen und durch steigende Energiepreise ernsthaft herausgefordert. Die Verbesserung der Energieeffizienz ist eine der größten Herausforderungen.

Das Ziel dieser Studie waren die Ermittlung und Bewertung der Energieeffizienz der Milchviehhaltung und der damit verbundenen Futterproduktion für im nordwestlichen Iran verbreitete Produktionssysteme. Im Iran sind Futterbaubetriebe und Milchviehbetriebe gewöhnlich vollständig getrennt. Für die Arbeit wurden Daten auf einem Futterbaubetrieb in der Moghanebene, im nordwestlichen Iran und auf 24 Milchviehbetrieben erfasst, die sich ebenfalls im nordwestlichen Iran befinden und sich in den Herdengrößen und Milcherträgen unterscheiden. Für diesen Zweck wurden ein Fragebogen ausgearbeitet und Daten über einen Zeitraum von drei Jahren erfasst. Es wurde eine Untersuchungsmethode erarbeitet, die auf der VDI-Richtlinie 4600 Kumulierter Energieaufwand (KEA) und dem ISO-Standard 14044 Umweltmanagement – Ökobilanz basiert, in dem Methoden zum Life Cycle Assessment (LCA) beschrieben sind. Die erarbeitete Methode ermöglicht es, die Energieeffizienz der Futtermittel- und der Milchproduktion einzeln zu analysieren und einzelne Betriebe zu vergleichen, die sich in der Herdengröße, im Milchertrag, beim Futter, im Haltungssystem und im Betriebsmanagement unterscheiden. Die Energieeffizienz wurde durch mehrere Indikatoren charakterisiert, wobei die Energieintensität (EI) und das Energie Output-Input-Verhältnis (OIR) die wichtigsten. Eine Sensitivitätsanalyse beschreibt die Unsicherheiten der Ergebnisse und identifiziert wichtige Felder für weitere Untersuchungen.

Die EI im untersuchten Futterproduktionsbetrieb (in MJ kg^{-1} DM) lag bei 2,92 für Luzerne, bei 6,76 für Gerste, bei 9,19 für Mais, bei 12,36 für Raps, bei 2,45 für Frühjahrsmaissilage, bei 4,45 für Sommermaissilage und bei 4,35 für Weizen. Von den untersuchten Futtermitteln war Frühjahrsmaissilage das vorteilhafteste, in Bezug auf alle Effizienzindikatoren, gefolgt von Luzerne und Weizen. Die Stickstoffdüngung, der Kraftstoffverbrauch und die Bewässerung waren die Hauptquellen des Energieeinsatzes in der Futtermittelproduktion, mit einem Anteil von jeweils etwa 32%, 28% und 20%. Die Zuordnung des Energieeinsatzes auf die Haupt- und die Nebenprodukte der Futtermittel erfolgte entsprechend dem Verhältnis ihrer metabolisierbaren Energie (MEV).

Die mittlere EI der in den untersuchten Betrieben produzierten, energiekorrigierten Milch (ECM) lag bei 5,84±0,69 MJ kg^{-1}, bei einer mittleren Milchleistung von 6 585±1 221 kg ECM Kuh^{-1} Jahr^{-1}. Die Futtermittel waren die Hauptquelle des Energie-Inputs in die Milchproduktion, mit einem Anteil von etwa 79 % des gesamten Energieaufwandes (67 % in der Milchviehfütterung und 12 % in der Färsenfütterung). Die Färsenaufzucht hatte einen Anteil von insgesamt 15 % (einschließlich der Fütterung; bei einer Reproduktionsrate von 0,25) und die direkte Energie hatte einen Anteil von 14 % am gesamten Energie-Input in die Milchproduktion. Der direkte Energieaufwand bestand zu 70 % aus Diesel- und Erdgasverbrauch für Heizung und Reinigung, und zu 30 % aus elektrischer Energie für Maschinen und Beleuchtung. Gebäude und Maschinen hatten jeweils einen Anteil von 3 % und 1 % am gesamten Energieaufwand der Milchproduktion. Die Sensivitätsanalyse hat bestätigt, dass der Energie-Input mit den Futtermitteln den größten Einfluss auf die Energieeffizienz in der Milchproduktion hat. Innerhalb der in den untersuchten Betrieben vorgefundenen Milchleistung (3 860-8 320 kg ECM Kuh^{-1} Jahr^{-1}) verringerte sich die EI bei steigender Milchleistung (-0,36 MJ kg^{-1} ECM je +1 000 kg ECM Kuh^{-1} Jahr^{-1}). Die Allokation des Energie-Inputs auf den Wirtschaftsdünger erfolgte auf Basis der Substitution von Mineraldünger und hatte dementsprechend einen Anteil von 15 % des gesamten Energieaufwandes zum Ergebnis. Die Aufteilung des verbliebenen Energie-Inputs zwischen Milch und Fleisch wurde anhand ihres oberen Heizwertes vorgenommen und führte zu einem Anteil am gesamten Energieaufwand von 83 % bzw. 2 %.

Die untersuchten Milchviehbetriebe hatten neben Milch auch Fleisch produziert, mit den verbliebenen Kälbern und weiteren Rindern. Die EI des mit Bullen bis zu einer Körpermasse von 400 kg produzierten Schlachtfleisches lag bei 75,4±9,1 MJ kg^{-1}, bei Fortführung der Mast bis zu einer Körpermasse von 700 kg lag sie bei 103,8±11,4 MJ kg^{-1}. Während die EI bei ersetzten, geschlachteten Milchkühen bei 16,3 MJ kg^{-1} Fleisch lag.

Die Kalkulation der EI auf Basis des oberen Heizwertes (Brennwert) der Futtermittel als Energieäquivalent, anstatt des zu ihrer Produktion erforderlichen KEA, führte zu einer mittleren EI in der Milchproduktion von 23,7±3,37 MJ kg^{-1} ECM und in der Erzeugung von Bullenfleisch (400 kg Körpermasse) 314±25 MJ kg^{-1}.

Das Energie Output-Input-Verhältnis (OIR), auf Basis des HHV, lag zwischen 2,03 MJ MJ^{-1} für Körnermais und 7,75 MJ MJ^{-1} für Frühjahrsmaissilage. Während OIR in der Milchproduktion 0,55 MJ MJ^{-1} und in der Fleischproduktion 0,12 MJ MJ^{-1} betrug. Dies unterstreicht, dass die Energieeffizienz in der Tierproduktion geringer ist als in der Pflanzenproduktion.

In der Literatur fanden sich geringere aber auch sehr ähnliche Werte für die EI in der Milcherzeugung. Weitere Forschungen sollten die Datenbasis erweitern und es ermöglichen Zielwerte abzuleiten und die Produktionsprozesse besser bewerten zu können als bisher.

چکیده

تقاضا برای فرآورده های دامی و مخصوصا شیری رو به افزایش است. این افزایش هم به دلیل رشد جمعیت و هم بدلیل افزایش استاندارهای زندگی صورت می گیرد. تولید جهانی محصولات شیری در سال ۲۰۵۰ میلادی دو برابر تولید سال ۱۹۹۹ پیش بینی شده است. جهت رسیدن به این سطح تولید پرورش گاو شیری در جهان در حال افزایش بوده و تراکم آن در واحد سطح بیشتر می شود که می تواند منجر به تراکم (شدت) انرژی بیشتر در تولیدات دامی شود و این در کشور ایران نیز صادق است. بهره وری انرژی در تولیدات دامی پایین تر از تولیدات گیاهی است. کشاورزی متراکم بصورت جدی تحت تاثیر مشکلات زیست محیطی، کاهش ذخایر سوختی و افزایش قیمت سوخت قرار دارد.

هدف این مطالعه برآورد و ارزیابی بهره وری انرژی در پرورش گاو شیری و تولید علوفه در سیستم های مرسوم در شمال غرب ایران بود. مزارع تولید علوفه و گاوداری ها در ایران کاملا از هم جدا هستند. داده های مربوط به تولید علوفه از کشت و صنعت مغان و داده های مربوط به پرورش گاو شیری از ۲۴ گاوداری با اندازه گله و عملکرد شیر متفاوت در شمال غرب ایران جمع آوری شدند. بدین منظور پرسش نامه هایی آماده و داده ها بر اساس این پرسش نامه ها و به مدت ۳ سال جمع آوری شدند. روش اصلی ارزیابی داده ها بر اساس روش نیاز تجمعی انرژی (CED) بود که توصیه شده توسط راهنمای ۴۶۰۰ انجمن مهندسان آلمان (VDI۴۶۰۰) و استاندارد ایزو ۱۴۰۴۴ برای ارزیابی چرخه زندگی (LCA) هست. این روش ها قادر ساختند تا ارزیابی بهره وری انرژی در تولید علوفه و پرورش گاو شیری بصورت جداگانه انجام گرفته و در جهت مقایسه محصولات مختلف علوفه ای و سپس گاوداری های با اندازه گله ها و عملکرد شیری متفاوت مورد مقایسه قرار گیرند. بهره وری انرژی با شاخص های متفاوتی سنجیده شد که مهمترین آنها شاخص تراکم (شدت) انرژی و شاخص بازده انرژی بودند. تحلیل حساسیت نیز بر اساس روش گاوسی برای عدم قطعیت ها و منابع آنها صورت گرفت.

تراکم انرژی در علوفه های مطالعه شده برای یونجه ۲/۹۲ ، برای جو ۶/۷۶ ، برای ذرت دانه ایی ۹/۱۹ ، برای کلزا ۱۲/۳۶، برای ذرت علوفه ایی کشت بهاره ۲/۴۵ ، برای ذرت علوفه ایی کشت تابستانه ۴/۴۵ و برای گندم ۴/۳۵ مگاژول به ازای هرکیلوگرم ماده خشک بود. ذرت علوفه ایی کشت بهاره از لحاظ همه شاخص ها در بین محصولات ارزیابی شده بهترین گیاه بود. و بعد از آن یونجه و گندم قرار داشتند. کود ازت، سوخت و آبیاری مهمترین منابع ورود انرژی در تولید محصولات بودند با سهم تقریبی به ترتیب ۳۲٪، ۲۸٪ و۲۰٪ از کل انرژی ورودی. انرژی ورودی در تولید محصولات علوفه ایی بر اساس نسبت انرژی متابولیسمی (MEV) بین محصول اصلی و محصول جانبی پخش شد.

تراکم انرژی میانگین در تولید شیر چربی و پروتئین اصلاح شده (ECM) برابر ۰/۶۹± ۵/۸۴ مگاژول به ازای هر کیلوگرم بر اساس انرژی سرمایه گذاری شده در آن (EEV) و برای عملکرد ۱۲۲۱± ۶۵۸۵ کیلوگرم شیر بر گاو سال محاسبه گردید. علوفه با سهم ۷۹٪ بیشترین انرژی ورودی در تولید شیر را داشت (۶۷٪ بصورت تغذیه مستقیم گاو شیری و ۱۲٪ بصورت غیر

مستقیم از طریق تغذیه تلیسه های جایگزین). جایگزینی تلیسه (با نرخ میانگین ۲۵٪) در حدود ۱۵٪ از کل انرژی ورودی در تولید شیر را بخود اختصاص می داد و بعد از آن انرژی های مستقیم با ۱۴٪ رتبه سوم را داشتند. ۷۰٪ انرژی مستقیم ورودی ناشی از مصرف سوخت های نفتی در گرمایش و شست شوی و ۳۰٪ در ماشین های الکتریکی و روشنایی بود. تاسیسات ساختمانی تنها ۳٪ و ماشین ها ۱٪ انرژی ورودی را شامل می شدند. تحلیل حساسیت سهم بزرگ انرژی ورودی از علوفه را در تولید شیر تایید کرد.

تراکم انرژی برای شیر در محدوده گاوداری های ارزیابی شده با افزایش عملکرد شیر کاهش می یافت (۰/۳۶- مگاژول به ازای هر کیلوگرم با افزایش ۱۰۰۰ کیلوگرم در عملکرد سالانه گاو). محدوده عملکرد شیر در گاوداری ها بین ۳۸۶۰ و ۸۳۲۰ کیلوگرم گاو سال بود. ۱۵٪ کل انرژی ورودی در تولید شیر با استفاده از روش جایگزینی به فضولات دامی اختصاص داده شد و با استفاده از مقایسه بین ارزش غذایی ۸۳٪ به شیر و ۲٪ به گوشت تولید شده از کشتار گاو های پیر اختصاص داده شد.

در کنار تولید شیر، در گاودای های شیری پرورش گاو گوشتی نیز انجام می گرفت. شدت انرژی در گوشت بدون استخوان تولید شده از گاو نر ۴۰۰ کیلویی، ۹/۱±۷۵/۴ و از گاو نر ۷۰۰ کیلویی ۱۱/۴±۱۰۳/۸ مگاژول بر کیلوگرم بود. شدت انرژی اختصاص داده شده به گوشت گاو شیری پیر ۱۶/۳ مگاژول بر کیلوگرم بود.

با محاسبه انرژی ورودی علوفه بر اساس ضریب انرژی بر پایه ارزش حرارتی بالا (HHV) ، تراکم انرژی برای شیر ۳/۳۷±۲۳/۷ و برای تولید گوشت از گاو نر ۴۰۰ کیلویی ۲۵±۳۱۴ مگاژول بر کیلوگرم محاسبه شد.

بازده انرژی در تولید محصولات گیاهی حداقل ۲/۰۳ در ذرت دانه ایی و ۷/۷۵ در ذرت علوفه ایی بهاره (مگاژول بر مگاژول) یرآورد شد، در حالیکه برای شیر ۰/۵۵ و برای گوشت ۰/۱۲ برآورد شد. این تاکید می کند که بهره وری انرژی در تولیدات دامی پایین تر از تولیدات گیاهی است.

در بررسی منابع، مقادیر کمتر یا مشابه تراکم انرژی برای تولید شیر مشاهده شد. تحقیقات بیشتری در این رابطه باید صورت گیرد تا داده های بیشتری جمع آوری و استنباطی از مقادیر هدف صورت گرفته و مراحل تولید را تحلیل نمود.

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Annexes

Annex 1.1. Energy input from machinery operations includes energy from materials, fuels and machine in the investigated crop productions (MJ ha^{-1} yr^{-1}).

Operation		*Products*						
		Alfalfa	*Barley*	*Maize corn*	*Rape-seed*	*Spring maize silage*	*Summer maize silage*	*Wheat*
Subsoiling	Amount	237	237	237	237	237	237	237
	%	<1	<1	<1	<1	<1	<1	<1
Manure Spreading	Amount	2,243	0	2,243	2,243	2243	0	2,243
	%	8	0	4	7	6	0	6
Ploughing	Amount	643	1,608	3,215	1,608	3,215	3,215	1,608
	%	2	5	6	5	9	10	4
Disking	Amount	774	2,903	2,903	2,903	2,903	2,903	2,903
	%	3	10	6	9	8	9	8
Levelling	Amount	420	1,050	2,101	2,101	2,101	2,101	2,101
	%	1	4	4	7	6	7	6
Ditching	Amount	213	213	213	213	213	213	213
	%	<1	<1	<1	<1	<1	<1	<1
Seeding	Amount	809	2,575	2,990	2,075	2,990	2,990	2,815
	%	3	9	6	7	8	10	8
Fertiliser Spreading	Amount	1,821	13,815	17,725	13,815	8,862	8,862	13,815
	%	6	48	34	44	24	28	39
Cultivatoring	Amount	0	0	1,303	0	1,303	434	0
	%	0	0	3	0	4	1	0
Spraying	Amount	1,271	464	5,145	349	0	0	577
	%	5	2	10	1	0	0	2
Irrigating	Amount	11,340	4,410	11,340	4,410	5,670	5,670	5,670
	%	40	15	22	14	15	18	16
Harvesting	Amount	6,913	1,353	1,794	1,428	3,571	2,806	1,710
	%	25	5	3	5	10	9	5
Straw Baling	Amount	0	492	0	0	0	0	984
	%	0	2	0	0	0	0	3
Transporting of yield	Amount	1,354	193	285	143	3,479	1,739	285
	%	5	<1	<1	<1	9	6	<1
Transporting of straw	Amount	0	271	0	0	0	0	572
	%	0	1	0	0	0	0	2
Total	**Amount**	**28,038**	**29,583**	**51,492**	**31,522**	**36,786**	**31,170**	**35,730**
	%	100	100	100	100	100	100	100

Annex 1.2. Energy input in the production of investigated crops according to different sources (MJ ha^{-1} yr^{-1}).

Operation		*Products*						
		Alfalfa	*Barley*	*Maize corn*	*Rapeseed*	*Spring maize silage*	*Summer maize silage*	*Wheat*
Fertiliser	Amount	1,721	13,480	17,390	13,480	8,695	8,695	13,480
	%	6	46	34	43	24	28	38
Fuel	Amount	9,095	7,012	11,691	7,714	13,679	10,683	9,091
	%	32	24	23	24	37	34	25
Irrigation	Amount	11,340	4,410	11,340	4,410	5,670	5,670	5,670
	%	40	15	22	14	15	18	16
Machinery	Amount	3,074	2,343	3,261	2,216	4,262	3,622	3,046
	%	11	8	6	7	12	12	9
Manure	Amount	1,980	0	1,980	1,980	1,980	0	1,980
	%	7	0	4	6	5	0	6
Pesticide	Amount	137	238	3331	122	0	0	123
	%	<1	<1	6	<1	0	0	<1
Seed	Amount	690	2,100	2,500	1,600	2,500	2,500	2,340
	%	2	7	5	5	7	7	7
Total	**Amount**	**28,038**	**29,583**	**51,492**	**31,522**	**36,786**	**31,170**	**35,730**
	%	100	100	100	100	100	100	100

Annex 2.1. Solutions for model tested for milk yield (kg ECM cow-1 yr-1) in regions 1-3.

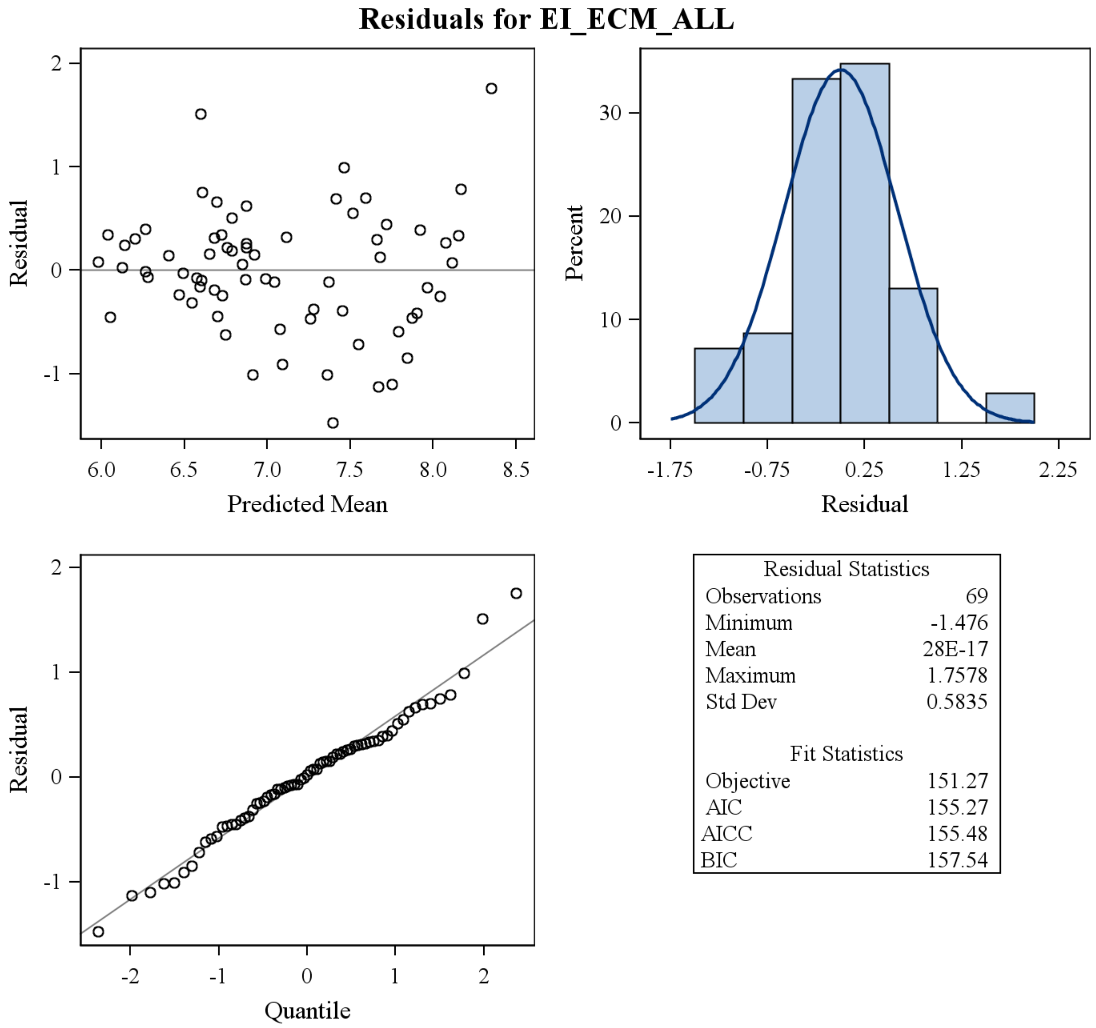
Solution for Fixed Effects							
Effect	Year	Region	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept			7746.41	600.78	38.1	12.89	<.0001
Year	2008		-36.1251	49.2411	39.6	-0.73	0.4675
Year	2009		-35.4085	47.6968	39.7	-0.74	0.4622
Year	2010		0	.	.	.	.
Region		1	1072.46	1684.04	61	0.64	0.5266
Region		2	-802.93	812.10	35.8	-0.99	0.3294
Region		3	0	.	.	.	.
Cow number			-52.0233	10.8246	41.5	-4.81	<.0001
Cow number * Region		1	-36.6154	62.0714	41.3	-0.59	0.5585
Cow number * Region		2	49.0001	14.5255	55	3.37	0.0014
Cow number * Region		3	0	.	.	.	.

Annex 2.2. Solutions for model tested for direct energy input in milk production (MJ kg-1 ECM) in regions 1-3 (without allocation).

Solution for Fixed Effects							
Effect	Year	Region	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept			1.7541	0.3552	29.2	4.94	<.0001
Year	2008		0.06604	0.02659	38.7	2.48	0.0174
Year	2009		0.04658	0.02664	39.1	1.75	0.0883
Year	2010		0	.	.	.	.
Region		1	-0.2098	0.2641	15.8	-0.79	0.4387
Region		2	0.3000	0.1804	15.4	1.66	0.1165
Region		3	0	.	.	.	.
ECM yield			-0.00011	0.000051	49.3	-2.26	0.0285
Cow number			-0.00544	0.003134	41.6	-1.74	0.0900

Annex 2.3. Solutions for model tested for total energy input in milk production (MJ kg-1 ECM) in regions 1-3 (without allocation).

Solution for Fixed Effects							
Effect	Year	Region	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept			9.9658	0.5466	20.8	18.23	<.0001
Year	2008		0.03928	0.1502	43.5	0.26	0.7949
Year	2009		-0.1098	0.1502	43.5	-0.73	0.4688
Year	2010		0	.	.	.	.
Region		1	-0.4858	0.3363	18.2	-1.44	0.1656
Region		2	0.4623	0.2235	17.9	2.07	0.0534
Region		3	0	.	.	.	.
ECM yield			-0.00045	0.000094	21.4	-4.85	<.0001
Cow number			-0.00246	0.005409	20.9	-0.45	0.6539



Residual Statistics	
Observations	69
Minimum	-1.476
Mean	28E-17
Maximum	1.7578
Std Dev	0.5835

Fit Statistics	
Objective	151.27
AIC	155.27
AICC	155.48
BIC	157.54

Annex 3. Residuals for model tested for energy input in ECM. Observation of the normal distribution, homogeneity and linearity of the residuals for model.

Annex 4. Active substances of consumed pesticides in the Moghan Agro-industry Company.

Product	*Pesticide trade name* [a]	*Pesticide active substance name* [a]	*Category* [a]	*Active substance (%)* [a]	*Dosage Mix formulation (l/ha)* [b]	*Dosage Active substance (kg/ha)* [b c]
Alfalfa	Eradicane	EPTC	Herbicide	82%	0.4	0.33
	Super galant	Haloxyfop-R methyl ester	Herbicide	10.8%	1	0.11
	Desis	Deltamethrin	Insecticide	2.5%	2	0.02
Barley	U46D	2-4-D	Herbicide	55%	1.5	0.83
Maize corn	U46D	2-4-D	Herbicide	55%	1.5	0.83
	Eradicane	EPTC	Herbicide	82%	5	4.10
	Gesaprim	Atrazine	Herbicide	80%	1.25	1.00
	Diacap	Diazinon	Insecticide	60%	10	6.00
	Omite	Propargite	Insecticide	57%	1.5	0.86
Rapeseed	Lontrel	Clopyralid	Herbicide	30%	0.75	0.23
	Focus	Cycloxydim	Herbicide	10%	2	0.20
Wheat	Topic	Clodinafop Propargyl	Herbicide	8%	0.9	0.07
	Granstar	Tribenuron-ethyl	Herbicide	75%	0.02	0.02
	Folicur	Tebuconazole	Fungicide	25%	2	0.5

[a] Anonymous (2012); [b] Consumed dosage in Moghan Company; Density of formulation assumed to be same as water (1 g/ml).

Annex 5 Collected input data from production of investigated crops in Moghan Agro-industrial Company and energy input (MJ ha^{-1} yr^{-1}) from each item.

Annex 5.1 Investigated crop: Alfalfa

Operation	*Item*	*Label*	*Unit*	*Count (unit)*	*Repeat (yr^{-1})*	*Duration (h)*	*Energy (MJ unit^{-1})*	*Life (h)*	*Energy (MJ ha^{-1} yr^{-1})*
Subsoiling	Tractor	MF6290	kg	6420.0	0.2	2.00	138.1	16000	22
Subsoiling	Machine	Ssoiler	kg	650.0	0.2	2.00	179.7	2000	23
Subsoiling	Fuel	Diesel	l	20.0	0.2	.	47.8	.	191
Subsoiling	Labour	Man	h	1.0	0.2	2.00	.	.	0
Manure spreading	Machine	Truck	kg	13000.0	0.2	1.00	138.1	12000	30
Manure spreading	Fuel	Diesel	l	4.4	0.2	.	47.8	.	42
Manure spreading	Labour	Man	h	1.0	0.2	1.00	.	.	0
Manure spreading	Tractor	MF399	kg	3317.0	0.2	1.00	138.1	16000	6
Manure spreading	Machine	Mspread	kg	3000.0	0.2	1.00	127.7	1500	51
Manure spreading	Fuel	Diesel	l	14.0	0.2	.	47.8	.	134
Manure spreading	Labour	Man	h	1.0	0.2	1.00	.	.	0
Manure spreading	Material	Manure	kg	30000.0	0.2	.	0.3	.	1980
Ploughing	Tractor	MF6290	kg	6420.0	0.4	2.50	138.1	16000	55
Ploughing	Machine	Plow	kg	1220.0	0.4	2.50	179.7	2000	110
Ploughing	Fuel	Diesel	l	25.0	0.4	.	47.8	.	478
Ploughing	Labour	Man	h	1.0	0.4	2.50	.	.	0
Disking	Tractor	MF6290	kg	6420.0	0.8	1.00	138.1	16000	44
Disking	Machine	Disk	kg	2950.0	0.8	1.00	148.5	2000	175
Disking	Fuel	Diesel	l	14.5	0.8	.	47.8	.	554
Disking	Labour	Man	h	1.0	0.8	1.00	.	.	0
Levelling	Tractor	MF6290	kg	6420.0	0.4	1.50	138.1	16000	33
Levelling	Machine	Leveler	kg	960.0	0.4	1.50	148.5	2000	43
Levelling	Fuel	Diesel	l	18.0	0.4	.	47.8	.	344
Levelling	Labour	Man	h	1.0	0.4	1.50	.	.	0
Ditching	Tractor	MF6290	kg	6420.0	1.0	0.33	138.1	16000	18
Ditching	Machine	Ditch	kg	125.0	1.0	0.33	148.5	2000	3
Ditching	Fuel	Diesel	l	4.0	1.0	.	47.8	.	191
Ditching	Labour	Man	h	1.0	1.0	0.33	.	.	0
Seeding	Tractor	MF399	kg	3317.0	0.2	1.00	138.1	16000	6
Seeding	Machine	Planter	kg	970.0	0.2	1.00	132.9	1500	17
Seeding	Fuel	Diesel	l	10.0	0.2	.	47.8	.	96
Seeding	Labour	Man	h	1.0	0.2	1.00	.	.	0
Seeding	Material	Seed	kg	15.0	0.2	.	230.0	.	690
Fertiliser spreading	Tractor	MF399	kg	3317.0	0.6	0.33	138.1	16000	6
Fertiliser spreading	Machine	Fspread	kg	520.0	0.6	0.33	127.7	1500	9

Fertiliser spreading	Fuel	Diesel	l	3.0	0.6	.	47.8	.	86
Fertiliser spreading	Labour	Man	h	1.0	0.6	0.33	.	.	0
Fertiliser spreading	Material	N	kg	50.0	0.2	.	78.2	.	782
Fertiliser spreading	Material	P2O5	kg	150.0	0.2	.	17.5	.	525
Fertiliser spreading	Material	K2O	kg	150.0	0.2	.	13.8	.	414
Spraying	Tractor	MF399	kg	3317.0	5.0	0.50	138.1	16000	72
Spraying	Machine	Chspread	kg	400.0	5.0	0.50	127.7	1200	106
Spraying	Fuel	Diesel	l	4.0	5.0	.	47.8	.	956
Spraying	Labour	Man	h	1.0	5.0	0.50	.	.	0
Spraying	Material	Herbicide	l	0.4	1.0	.	288.0	.	126
Spraying	Material	Insecticide	l	0.1	1.0	.	237.0	.	12
Spraying	Material	Fungicide	l	0.0	0.0	.	196.0	.	0
Cultivatoring	Tractor	MF399	kg	3317.0	0.0	0.00	138.1	16000	0
Cultivatoring	Machine	field	kg	320.0	0.0	0.00	139.8	2000	0
Cultivatoring	Fuel	Diesel	l	8.0	0.0	.	47.8	.	0
Cultivatoring	Labour	Man	h	1.0	0.0	0.00	.	.	0
Harvesting	Tractor	MF399	kg	3317.0	5.0	4.00	138.1	16000	573
Harvesting	Machine	Mower	kg	350.0	5.0	2.00	220.5	2000	386
Harvesting	Machine	Racker	kg	165.0	5.0	1.00	129.4	2000	53
Harvesting	Machine	Baler	kg	1560.0	5.0	1.00	129.4	2500	404
Harvesting	Fuel	Diesel	l	23.0	5.0	.	47.8	.	5497
Harvesting	Labour	Man	h	1.0	5.0	4.00	.	.	0
Transport yield	Machine	Trailer	kg	18000.0	5.0	0.80	138.1	12000	829
Transport yield	Fuel	Diesel	l	2.2	5.0	.	47.8	.	526
Transport yield	Labour	Man	h	6.0	5.0	0.70	.	.	0
Irrigating	Material	Water	m3	2250.0	8.0	.	0.6	.	11340
Irrigating	Labour	Man	h	1.0	8.0	2.00	.	.	0

Annex 5.2 Investigated crop: Barley

Operation	*Item*	*Label*	*Unit*	*Count (unit)*	*Repeat (yr^{-1})*	*Duration (h)*	*Energy (MJ $unit^{-1}$)*	*Life (h)*	*Energy (MJ ha^{-1} yr^{-1})*
Subsoiling	Tractor	MF6290	kg	6420.0	0.2	2.00	138.1	16000	22
Subsoiling	Machine	Ssoiler	kg	650.0	0.2	2.00	179.7	2000	23
Subsoiling	Fuel	Diesel	l	20.0	0.2	.	47.8	.	191
Subsoiling	Labour	Man	h	1.0	0.2	2.00	.	.	0
Manure spreading	Machine	Truck	kg	13000.0	0.0	0.00	138.1	12000	0
Manure spreading	Fuel	Diesel	l	4.4	0.0	.	47.8	.	0
Manure spreading	Labour	Man	h	1.0	0.0	0.00	.	.	0
Manure spreading	Tractor	MF399	kg	3317.0	0.0	0.00	138.1	16000	0
Manure spreading	Machine	Mspread	kg	0.0	0.0	0.00	127.7	1500	0
Manure spreading	Fuel	Diesel	l	14.0	0.0	.	47.8	.	0
Manure spreading	Labour	Man	h	0.0	0.0	0.00	.	.	0
Manure spreading	Material	Manure	kg	0.0	0.0	.	0.3	.	0
Ploughing	Tractor	MF6290	kg	6420.0	1.0	2.50	138.1	16000	139
Ploughing	Machine	Plow	kg	1220.0	1.0	2.50	179.7	2000	274
Ploughing	Fuel	Diesel	l	25.0	1.0	.	47.8	.	1195
Ploughing	Labour	Man	h	1.0	1.0	2.50	.	.	0
Disking	Tractor	MF6290	kg	6420.0	3.0	1.00	138.1	16000	166
Disking	Machine	Disk	kg	2950.0	3.0	1.00	148.5	2000	657
Disking	Fuel	Diesel	l	14.5	3.0	.	47.8	.	2079
Disking	Labour	Man	h	1.0	3.0	1.00	.	.	0
Levelling	Tractor	MF6290	kg	6420.0	1.0	1.50	138.1	16000	83
Levelling	Machine	Leveler	kg	960.0	1.0	1.50	148.5	2000	107
Levelling	Fuel	Diesel	l	18.0	1.0	.	47.8	.	860
Levelling	Labour	Man	h	1.0	1.0	1.50	.	.	0
Ditching	Tractor	MF6290	kg	6420.0	1.0	0.33	138.1	16000	18
Ditching	Machine	Ditch	kg	125.0	1.0	0.33	148.5	2000	3
Ditching	Fuel	Diesel	l	4.0	1.0	.	47.8	.	191
Ditching	Labour	Man	h	1.0	1.0	0.33	.	.	0
Seeding	Tractor	MF399	kg	3317.0	1.0	1.00	138.1	16000	29
Seeding	Machine	Planter	kg	720.0	1.0	1.00	132.9	1500	64
Seeding	Fuel	Diesel	l	8.0	1.0	.	47.8	.	382
Seeding	Labour	Man	h	1.0	1.0	1.00	.	.	0
Seeding	Material	Seed	kg	150.0	1.0	.	14.0	.	2100
Fertiliser spreading	Tractor	MF399	kg	3317.0	2.0	0.33	138.1	16000	19
Fertiliser spreading	Machine	Fspread	kg	520.0	2.0	0.33	127.7	1500	29
Fertiliser spreading	Fuel	Diesel	l	3.0	2.0	.	47.8	.	287
Fertiliser spreading	Labour	Man	h	1.0	2.0	0.33	.	.	0

Fertiliser spreading	Material	N	kg	75.0	2.0	.	78.2	.	11730
Fertiliser spreading	Material	P2O5	kg	100.0	1.0	.	17.5	.	1750
Fertiliser spreading	Material	K2O	kg	0.0	0.0	.	13.8	.	0
Spraying	Tractor	MF399	kg	3317.0	1.0	0.50	138.1	16000	14
Spraying	Machine	Chspread	kg	400.0	1.0	0.50	127.7	1200	21
Spraying	Fuel	Diesel	l	4.0	1.0	.	47.8	.	191
Spraying	Labour	Man	h	1.0	1.0	0.50	.	.	0
Spraying	Material	Herbicide	l	0.8	1.0	.	288.0	.	238
Spraying	Material	Insecticide	l	0.0	0.0	.	237.0	.	0
Spraying	Material	Fungicide	l	0.0	0.0	.	196.0	.	0
Cultivatoring	Tractor	MF399	kg	3317.0	0.0	0.00	138.1	16000	0
Cultivatoring	Machine	field	kg	320.0	0.0	0.00	139.8	2000	0
Cultivatoring	Fuel	Diesel	l	8.0	0.0	.	47.8	.	0
Cultivatoring	Labour	Man	h	1.0	0.0	0.00	.	.	0
Harvesting	Machine	Com. JD955	kg	6000.0	1.0	1.50	116.4	3000	349
Harvesting	Fuel	Diesel	l	21.0	1.0	.	47.8	.	1004
Harvesting	Labour	Man	h	1.0	1.0	1.50	.	.	0
Straw baling	Tractor	MF399	kg	3317.0	1.0	1.00	138.1	16000	29
Straw baling	Machine	Baler	kg	1560.0	1.0	1.00	129.4	2500	81
Straw baling	Fuel	Diesel	l	8.0	1.0	.	47.8	.	382
Straw baling	Labour	Man	h	1.0	1.0	1.00	.	.	0
Transport yield	Machine	Truck	kg	13000.0	1.0	0.33	138.1	12000	49
Transport yield	Fuel	Diesel	l	3.0	1.0	.	47.8	.	143
Transport yield	Labour	Man	h	1.0	1.0	0.33	.	.	0
Transport straw	Machine	Trailer	kg	18000.0	1.0	0.80	138.1	12000	166
Transport straw	Fuel	Diesel	l	2.2	1.0	.	47.8	.	105
Transport straw	Labour	Man	h	6.0	1.0	0.70	.	.	0
Irrigating	Material	Water	m3	1750.0	4.0	.	0.6	.	4410
Irrigating	Labour	Man	h	1.0	4.0	2.00	.	.	0

Annex 5.3 Investigated crop: Maize corn

Operation	*Item*	*Label*	*Unit*	*Count* (unit)	*Repeat* (yr^{-1})	*Duration* (h)	*Energy* (MJ $unit^{-1}$)	*Life* (h)	*Energy* (MJ ha^{-1} yr^{-1})
Subsoiling	Tractor	MF6290	kg	6420.0	0.2	2.00	138.1	16000	22
Subsoiling	Machine	Ssoiler	kg	650.0	0.2	2.00	179.7	2000	23
Subsoiling	Fuel	Diesel	l	20.0	0.2	.	47.8	.	191
Subsoiling	Labour	Man	h	1.0	0.2	2.00	.	.	0
Manure spreading	Machine	Truck	kg	13000.0	0.2	1.00	138.1	12000	30
Manure spreading	Fuel	Diesel	l	4.4	0.2	.	47.8	.	42
Manure spreading	Labour	Man	h	1.0	0.2	1.00	.	.	0
Manure spreading	Tractor	MF399	kg	3317.0	0.2	1.00	138.1	16000	6
Manure spreading	Machine	Mspread	kg	3000.0	0.2	1.00	127.7	1500	51
Manure spreading	Fuel	Diesel	l	14.0	0.2	.	47.8	.	134
Manure spreading	Labour	Man	h	1.0	0.2	1.00	.	.	0
Manure spreading	Material	Manure	kg	30000.0	0.2	.	0.3	.	1980
Ploughing	Tractor	MF6290	kg	6420.0	2.0	2.50	138.1	16000	277
Ploughing	Machine	Plow	kg	1220.0	2.0	2.50	179.7	2000	548
Ploughing	Fuel	Diesel	l	25.0	2.0	.	47.8	.	2390
Ploughing	Labour	Man	h	1.0	2.0	2.50	.	.	0
Disking	Tractor	MF6290	kg	6420.0	3.0	1.00	138.1	16000	166
Disking	Machine	Disk	kg	2950.0	3.0	1.00	148.5	2000	657
Disking	Fuel	Diesel	l	14.5	3.0	.	47.8	.	2079
Disking	Labour	Man	h	1.0	3.0	1.00	.	.	0
Levelling	Tractor	MF6290	kg	6420.0	2.0	1.50	138.1	16000	166
Levelling	Machine	Leveler	kg	960.0	2.0	1.50	148.5	2000	214
Levelling	Fuel	Diesel	l	18.0	2.0	.	47.8	.	1721
Levelling	Labour	Man	h	1.0	2.0	1.50	.	.	0
Ditching	Tractor	MF6290	kg	6420.0	1.0	0.33	138.1	16000	18
Ditching	Machine	Ditch	kg	125.0	1.0	0.33	148.5	2000	3
Ditching	Fuel	Diesel	l	4.0	1.0	.	47.8	.	191
Ditching	Labour	Man	h	1.0	1.0	0.33	.	.	0
Seeding	Tractor	MF399	kg	3317.0	1.0	1.00	138.1	16000	29
Seeding	Machine	Planter	kg	890.0	1.0	1.00	132.9	1500	79
Seeding	Fuel	Diesel	l	8.0	1.0	.	47.8	.	382
Seeding	Labour	Man	h	1.0	1.0	1.00	.	.	0
Seeding	Material	Seed	kg	25.0	1.0	.	100.0	.	2500
Fertiliser spreading	Tractor	MF399	kg	3317.0	2.0	0.33	138.1	16000	19
Fertiliser spreading	Machine	Fspread	kg	520.0	2.0	0.33	127.7	1500	29
Fertiliser spreading	Fuel	Diesel	l	3.0	2.0	.	47.8	.	287
Fertiliser spreading	Labour	Man	h	1.0	2.0	0.33	.	.	0

Fertiliser spreading	Material	N	kg	100.0	2.0	.	78.2	.	15640
Fertiliser spreading	Material	P2O5	kg	100.0	1.0	.	17.5	.	1750
Fertiliser spreading	Material	K2O	kg	0.0	0.0	.	13.8	.	0
Spraying	Tractor	MF399	kg	3317.0	8.0	0.50	138.1	16000	115
Spraying	Machine	Chspread	kg	400.0	8.0	0.50	127.7	1200	170
Spraying	Fuel	Diesel	l	4.0	8.0	.	47.8	.	1530
Spraying	Labour	Man	h	1.0	8.0	0.50	.	.	0
Spraying	Material	Herbicide	l	5.9	1.0	.	288.0	.	1706
Spraying	Material	Insecticide	l	6.9	1.0	.	237.0	.	1625
Spraying	Material	Fungicide	l	0.0	0.0	.	196.0	.	0
Cultivatoring	Tractor	MF399	kg	3317.0	3.0	1.00	138.1	16000	86
Cultivatoring	Machine	row	kg	320.0	3.0	1.00	145.9	2000	70
Cultivatoring	Fuel	Diesel	l	8.0	3.0	.	47.8	.	1147
Cultivatoring	Labour	Man	h	1.0	3.0	1.00	.	.	0
Harvesting	Machine	Com. jd955	kg	6000.0	1.0	1.75	116.4	3000	407
Harvesting	Fuel	Diesel	l	29.0	1.0	.	47.8	.	1386
Harvesting	Labour	Man	h	1.0	1.0	1.75	.	.	0
Transport yield	Machine	Truck	kg	13000.0	1.0	0.50	138.1	12000	75
Transport yield	Fuel	Diesel	l	4.4	1.0	.	47.8	.	210
Transport yield	Labour	Man	h	1.0	1.0	0.50	.	.	0
Irrigating	Material	Water	m3	2250.0	8.0	.	0.6	.	11340
Irrigating	Labour	Man	h	1.0	8.0	2.50	.	.	0

Annex 5.4 Investigated crop: Rapeseed

Operation	*Item*	*Label*	*Unit*	*Count (unit)*	*Repeat (yr^{-1})*	*Duration (h)*	*Energy (MJ $unit^{-1}$)*	*Life (h)*	*Energy (MJ ha^{-1} yr^{-1})*
Subsoiling	Tractor	MF6290	kg	6420.0	0.2	2.00	138.1	16000	22
Subsoiling	Machine	Ssoiler	kg	650.0	0.2	2.00	179.7	2000	23
Subsoiling	Fuel	Diesel	l	20.0	0.2	.	47.8	.	191
Subsoiling	Labour	Man	h	1.0	0.2	2.00	.	.	0
Manure spreading	Machine	Truck	kg	13000.0	0.2	1.00	138.1	12000	30
Manure spreading	Fuel	Diesel	l	4.4	0.2	.	47.8	.	42
Manure spreading	Labour	Man	h	1.0	0.2	1.00	.	.	0
Manure spreading	Tractor	MF399	kg	3317.0	0.2	1.00	138.1	16000	6
Manure spreading	Machine	Mspread	kg	3000.0	0.2	1.00	127.7	1500	51
Manure spreading	Fuel	Diesel	l	14.0	0.2	.	47.8	.	134
Manure spreading	Labour	Man	h	1.0	0.2	1.00	.	.	0
Manure spreading	Material	Manure	kg	30000.0	0.2	.	0.3	.	1980
Ploughing	Tractor	MF6290	kg	6420.0	1.0	2.50	138.1	16000	139
Ploughing	Machine	Plow	kg	1220.0	1.0	2.50	179.7	2000	274
Ploughing	Fuel	Diesel	l	25.0	1.0	.	47.8	.	1195
Ploughing	Labour	Man	h	1.0	1.0	2.50	.	.	0
Disking	Tractor	MF6290	kg	6420.0	3.0	1.00	138.1	16000	166
Disking	Machine	Disk	kg	2950.0	3.0	1.00	148.5	2000	657
Disking	Fuel	Diesel	l	14.5	3.0	.	47.8	.	2079
Disking	Labour	Man	h	1.0	3.0	1.00	.	.	0
Levelling	Tractor	MF6290	kg	6420.0	2.0	1.50	138.1	16000	166
Levelling	Machine	Leveler	kg	960.0	2.0	1.50	148.5	2000	214
Levelling	Fuel	Diesel	l	18.0	2.0	.	47.8	.	1721
Levelling	Labour	Man	h	1.0	2.0	1.50	.	.	0
Ditching	Tractor	MF6290	kg	6420.0	1.0	0.33	138.1	16000	18
Ditching	Machine	Ditch	kg	125.0	1.0	0.33	148.5	2000	3
Ditching	Fuel	Diesel	l	4.0	1.0	.	47.8	.	191
Ditching	Labour	Man	h	1.0	1.0	0.33	.	.	0
Seeding	Tractor	MF399	kg	3317.0	1.0	1.00	138.1	16000	29
Seeding	Machine	Planter	kg	720.0	1.0	1.00	132.9	1500	64
Seeding	Fuel	Diesel	l	8.0	1.0	.	47.8	.	382
Seeding	Labour	Man	h	1.0	1.0	1.00	.	.	0
Seeding	Material	Seed	kg	8.0	1.0	.	200.0	.	1600
Fertiliser spreading	Tractor	MF399	kg	3317.0	2.0	0.33	138.1	16000	19
Fertiliser spreading	Machine	Fspread	kg	520.0	2.0	0.33	127.7	1500	29
Fertiliser spreading	Fuel	Diesel	l	3.0	2.0	.	47.8	.	287
Fertiliser spreading	Labour	Man	h	1.0	2.0	0.33	.	.	0

Fertiliser spreading	Material	N	kg	75.0	2.0	.	78.2	.	11730
Fertiliser spreading	Material	P2O5	kg	100.0	1.0	.	17.5	.	1750
Fertiliser spreading	Material	K2O	kg	0.0	0.0	.	13.8	.	0
Spraying	Tractor	MF399	kg	3317.0	1.0	0.50	138.1	16000	14
Spraying	Machine	Chspread	kg	400.0	1.0	0.50	127.7	1200	21
Spraying	Fuel	Diesel	l	4.0	1.0	.	47.8	.	191
Spraying	Labour	Man	h	1.0	1.0	0.50	.	.	0
Spraying	Material	Herbicide	l	0.4	1.0	.	288.0	.	122
Spraying	Material	Insecticide	l	0.0	0.0	.	237.0	.	0
Spraying	Material	Fungicide	l	0.0	0.0	.	196.0	.	0
Cultivatoring	Tractor	MF399	kg	3317.0	0.0	0.00	138.1	16000	0
Cultivatoring	Machine	field	kg	320.0	0.0	0.00	139.8	2000	0
Cultivatoring	Fuel	Diesel	l	8.0	0.0	.	47.8	.	0
Cultivatoring	Labour	Man	h	1.0	0.0	0.00	.	.	0
Harvesting	Machine	Com. jd955	kg	6000.0	1.0	1.00	116.4	3000	233
Harvesting	Fuel	Diesel	l	25.0	1.0	.	47.8	.	1195
Harvesting	Labour	Man	h	1.0	1.0	1.00	.	.	0
Transport yield	Machine	Truck	kg	13000.0	1.0	0.25	138.1	12000	37
Transport yield	Fuel	Diesel	l	2.2	1.0	.	47.8	.	105
Transport yield	Labour	Man	h	1.0	1.0	0.25	.	.	0
Irrigating	Material	Water	m3	875.0	8.0	.	0.6	.	4410
Irrigating	Labour	Man	h	1.0	4.0	2.00	.	.	0

Annex 5.5 Investigated crop: Spring maize silage

Operation	*Item*	*Label*	*Unit*	*Count (unit)*	*Repeat* (*yr*$^{-1}$)	*Duration (h)*	*Energy (MJ unit*$^{-1}$*)*	*Life (h)*	*Energy (MJ ha*$^{-1}$ *yr*$^{-1}$*)*
Subsoiling	Tractor	MF6290	kg	6420.0	0.2	2.00	138.1	16000	22
Subsoiling	Machine	Ssoiler	kg	650.0	0.2	2.00	179.7	2000	23
Subsoiling	Fuel	Diesel	l	20.0	0.2	.	47.8	.	191
Subsoiling	Labour	Man	h	1.0	0.2	2.00	.	.	0
Manure spreading	Machine	Truck	kg	13000.0	0.2	1.00	138.1	12000	30
Manure spreading	Fuel	Diesel	l	4.4	0.2	.	47.8	.	42
Manure spreading	Labour	Man	h	1.0	0.2	1.00	.	.	0
Manure spreading	Tractor	MF399	kg	3317.0	0.2	1.00	138.1	16000	6
Manure spreading	Machine	Mspread	kg	3000.0	0.2	1.00	127.7	1500	51
Manure spreading	Fuel	Diesel	l	14.0	0.2	.	47.8	.	134
Manure spreading	Labour	Man	h	1.0	0.2	1.00	.	.	0
Manure spreading	Material	Manure	kg	30000.0	0.2	.	0.3	.	1980
Ploughing	Tractor	MF6290	kg	6420.0	2.0	2.50	138.1	16000	277
Ploughing	Machine	Plow	kg	1220.0	2.0	2.50	179.7	2000	548
Ploughing	Fuel	Diesel	l	25.0	2.0	.	47.8	.	2390
Ploughing	Labour	Man	h	1.0	2.0	2.50	.	.	0
Disking	Tractor	MF6290	kg	6420.0	3.0	1.00	138.1	16000	166
Disking	Machine	Disk	kg	2950.0	3.0	1.00	148.5	2000	657
Disking	Fuel	Diesel	l	14.5	3.0	.	47.8	.	2079
Disking	Labour	Man	h	1.0	3.0	1.00	.	.	0
Levelling	Tractor	MF6290	kg	6420.0	2.0	1.50	138.1	16000	166
Levelling	Machine	Leveler	kg	960.0	2.0	1.50	148.5	2000	214
Levelling	Fuel	Diesel	l	18.0	2.0	.	47.8	.	1721
Levelling	Labour	Man	h	1.0	2.0	1.50	.	.	0
Ditching	Tractor	MF6290	kg	6420.0	1.0	0.33	138.1	16000	18
Ditching	Machine	Ditch	kg	125.0	1.0	0.33	148.5	2000	3
Ditching	Fuel	Diesel	l	4.0	1.0	.	47.8	.	191
Ditching	Labour	Man	h	1.0	1.0	0.33	.	.	0
Seeding	Tractor	MF399	kg	3317.0	1.0	1.00	138.1	16000	29

Seeding	Machine	Planter	kg	890.0	1.0	1.00	132.9	1500	79
Seeding	Fuel	Diesel	l	8.0	1.0	.	47.8	.	382
Seeding	Labour	Man	h	1.0	1.0	1.00	.	.	0
Seeding	Material	Seed	kg	25.0	1.0	.	100.0	.	2500
Fertiliser spreading	Tractor	MF399	kg	3317.0	1.0	0.33	138.1	16000	9
Fertiliser spreading	Machine	Fspread	kg	520.0	1.0	0.33	127.7	1500	15
Fertiliser spreading	Fuel	Diesel	l	3.0	1.0	.	47.8	.	143
Fertiliser spreading	Labour	Man	h	1.0	1.0	0.33	.	.	0
Fertiliser spreading	Material	N	kg	100.0	1.0	.	78.2	.	7820
Fertiliser spreading	Material	P2O5	kg	50.0	1.0	.	17.5	.	875
Fertiliser spreading	Material	K2O	kg	0.0	0.0	.	13.8	.	0
Spraying	Tractor	MF399	kg	3317.0	0.0	0.00	138.1	16000	0
Spraying	Machine	Chspread	kg	400.0	0.0	0.00	127.7	1200	0
Spraying	Fuel	Diesel	l	4.8	0.0	.	47.8	.	0
Spraying	Labour	Man	h	1.0	0.0	0.00	.	.	0
Spraying	Material	Herbicide	l	0.0	0.0	.	288.0	.	0
Spraying	Material	Insecticide	l	0.0	0.0	.	237.0	.	0
Spraying	Material	Fungicide	l	0.0	0.0	.	196.0	.	0
Cultivatoring	Tractor	MF399	kg	3317.0	3.0	1.00	138.1	16000	86
Cultivatoring	Machine	row	kg	320.0	3.0	1.00	145.9	2000	70
Cultivatoring	Fuel	Diesel	l	8.0	3.0	.	47.8	.	1147
Cultivatoring	Labour	Man	h	1.0	3.0	1.00	.	.	0
Harvesting	Machine	Chop. Jag682	kg	7200.0	1.0	2.00	124.2	2000	894
Harvesting	Fuel	Diesel	l	56.0	1.0	.	47.8	.	2677
Harvesting	Labour	Man	h	1.0	1.0	2.00	.	.	0
Transport yield	Machine	Truck	kg	13000.0	6.0	1.00	138.1	12000	898
Transport yield	Fuel	Diesel	l	9.0	6.0	.	47.8	.	2581
Transport yield	Labour	Man	h	1.0	6.0	1.00	.	.	0
Irrigating	Material	Water	m3	2250.0	4.0	.	0.6	.	5670
Irrigating	Labour	Man	h	1.0	4.0	2.50	.	.	0

Annex 5.6 Investigated crop: Summer maize silage

Operation	*Item*	*Label*	*Unit*	*Count (unit)*	*Repeat (yr^{-1})*	*Duration (h)*	*Energy (MJ $unit^{-1}$)*	*Life (h)*	*Energy (MJ ha^{-1} yr^{-1})*
Subsoiling	Tractor	MF6290	kg	6420.0	0.2	2.00	138.1	16000	22
Subsoiling	Machine	Ssoiler	kg	650.0	0.2	2.00	179.7	2000	23
Subsoiling	Fuel	Diesel	l	20.0	0.2	.	47.8	.	191
Subsoiling	Labour	Man	h	1.0	0.2	2.00	.	.	0
Manure spreading	Machine	Truck	kg	13000.0	0.0	0.00	138.1	12000	0
Manure spreading	Fuel	Diesel	l	4.4	0.0	.	47.8	.	0
Manure spreading	Labour	Man	h	1.0	0.0	0.00	.	.	0
Manure spreading	Tractor	MF399	kg	3317.0	0.0	0.00	138.1	16000	0
Manure spreading	Machine	Mspread	kg	3000.0	0.0	0.00	127.7	1500	0
Manure spreading	Fuel	Diesel	l	14.0	0.0	.	47.8	.	0
Manure spreading	Labour	Man	h	1.0	0.0	0.00	.	.	0
Manure spreading	Material	Manure	kg	0.0	0.0	0.00	0.3	.	0
Ploughing	Tractor	MF6290	kg	6420.0	2.0	2.50	138.1	16000	277
Ploughing	Machine	Plow	kg	1220.0	2.0	2.50	179.7	2000	548
Ploughing	Fuel	Diesel	l	25.0	2.0	.	47.8	.	2390
Ploughing	Labour	Man	h	1.0	2.0	2.50	.	.	0
Disking	Tractor	MF6290	kg	6420.0	3.0	1.00	138.1	16000	166
Disking	Machine	Disk	kg	2950.0	3.0	1.00	148.5	2000	657
Disking	Fuel	Diesel	l	14.5	3.0	.	47.8	.	2079
Disking	Labour	Man	h	1.0	3.0	1.00	.	.	0
Levelling	Tractor	MF6290	kg	6420.0	2.0	1.50	138.1	16000	166
Levelling	Machine	Leveler	kg	960.0	2.0	1.50	148.5	2000	214
Levelling	Fuel	Diesel	l	18.0	2.0	.	47.8	.	1721
Levelling	Labour	Man	h	1.0	2.0	1.50	.	.	0
Ditching	Tractor	MF6290	kg	6420.0	1.0	0.33	138.1	16000	18
Ditching	Machine	Ditch	kg	125.0	1.0	0.33	148.5	2000	3
Ditching	Fuel	Diesel	l	4.0	1.0	.	47.8	.	191
Ditching	Labour	Man	h	1.0	1.0	0.33	.	.	0
Seeding	Tractor	MF399	kg	3317.0	1.0	1.00	138.1	16000	29
Seeding	Machine	Planter	kg	890.0	1.0	1.00	132.9	1500	79
Seeding	Fuel	Diesel	l	8.0	1.0	.	47.8	.	382
Seeding	Labour	Man	h	1.0	1.0	1.00	.	.	0

Seeding	Material	Seed	kg	25.0	1.0	.	100.0	.	2500
Fertiliser spreading	Tractor	MF399	kg	3317.0	1.0	0.33	138.1	16000	9
Fertiliser spreading	Machine	Fspread	kg	520.0	1.0	0.33	127.7	1500	15
Fertiliser spreading	Fuel	Diesel	l	3.0	1.0	.	47.8	.	143
Fertiliser spreading	Labour	Man	h	1.0	1.0	0.33	.	.	0
Fertiliser spreading	Material	N	kg	100.0	1.0	.	78.2	.	7820
Fertiliser spreading	Material	P2O5	kg	50.0	1.0	.	17.5	.	875
Fertiliser spreading	Material	K2O	kg	0.0	0.0	.	13.8	.	0
Spraying	Tractor	MF399	kg	3317.0	0.0	0.00	138.1	16000	0
Spraying	Machine	Chspread	kg	400.0	0.0	0.00	127.7	1200	0
Spraying	Fuel	Diesel	l	4.0	0.0	.	47.8	.	0
Spraying	Labour	Man	h	1.0	0.0	0.00	.	.	0
Spraying	Material	Herbicide	l	0.0	0.0	.	288.0	.	0
Spraying	Material	Insecticide	l	0.0	0.0	.	237.0	.	0
Spraying	Material	Fungicide	l	0.0	0.0	.	196.0	.	0
Cultivatoring	Tractor	MF399	kg	3317.0	1.0	1.00	138.1	16000	29
Cultivatoring	Machine	row	kg	320.0	1.0	1.00	145.9	2000	23
Cultivatoring	Fuel	Diesel	l	8.0	1.0	.	47.8	.	382
Cultivatoring	Labour	Man	h	1.0	1.0	1.00	.	.	0
Harvesting	Machine	Chop. Jag682	kg	7200.0	1.0	2.00	124.2	2000	894
Harvesting	Fuel	Diesel	l	40.0	1.0	.	47.8	.	1912
Harvesting	Labour	Man	h	1.0	1.0	2.00	.	.	0
Transport yield	Machine	Truck	kg	13000.0	3.0	1.00	138.1	12000	449
Transport yield	Fuel	Diesel	l	9.0	3.0	.	47.8	.	1291
Transport yield	Labour	Man	h	1.0	3.0	1.00	.	.	0
Irrigating	Material	Water	m3	2250.0	4.0	.	0.6	.	5670
Irrigating	Labour	Man	h	1.0	4.0	2.50	.	.	0

Annex 5.7 Investigated crop: Wheat

Operation	*Item*	*Label*	*Unit*	*Count* *(unit)*	*Repeat* *(yr^{-1})*	*Duration* *(h)*	*Energy* *(MJ unit^{-1})*	*Life* *(h)*	*Energy* *(MJ ha^{-1} yr^{-1})*
Subsoiling	Tractor	MF6290	kg	6420.0	0.2	2.00	138.1	16000	22
Subsoiling	Machine	Ssoiler	kg	650.0	0.2	2.00	179.7	2000	23
Subsoiling	Fuel	Diesel	l	20.0	0.2	.	47.8	.	191
Subsoiling	Labour	Man	h	1.0	0.2	2.00	.	.	0
Manure spreading	Machine	Truck	kg	13000.0	0.2	1.00	138.1	12000	30
Manure spreading	Fuel	Diesel	l	4.4	0.2	.	47.8	.	42
Manure spreading	Labour	Man	h	1.0	0.2	1.00	.	.	0
Manure spreading	Tractor	MF399	kg	3317.0	0.2	1.00	138.1	16000	6
Manure spreading	Machine	Mspread	kg	3000.0	0.2	1.00	127.7	1500	51
Manure spreading	Fuel	Diesel	l	14.0	0.2	.	47.8	.	134
Manure spreading	Labour	Man	h	1.0	0.2	1.00	.	.	0
Manure spreading	Material	Manure	kg	30000.0	0.2	.	0.3	.	1980
Ploughing	Tractor	MF6290	kg	6420.0	1.0	2.50	138.1	16000	139
Ploughing	Machine	Plow	kg	1220.0	1.0	2.50	179.7	2000	274
Ploughing	Fuel	Diesel	l	25.0	1.0	.	47.8	.	1195
Ploughing	Labour	Man	h	1.0	1.0	2.50	.	.	0
Disking	Tractor	MF6290	kg	6420.0	3.0	1.00	138.1	16000	166
Disking	Machine	Disk	kg	2950.0	3.0	1.00	148.5	2000	657
Disking	Fuel	Diesel	l	14.5	3.0	.	47.8	.	2079
Disking	Labour	Man	h	1.0	3.0	1.00	.	.	0
Levelling	Tractor	MF6290	kg	6420.0	2.0	1.50	138.1	16000	166
Levelling	Machine	Leveler	kg	960.0	2.0	1.50	148.5	2000	214
Levelling	Fuel	Diesel	l	18.0	2.0	.	47.8	.	1721
Levelling	Labour	Man	h	1.0	2.0	1.50	.	.	0
Ditching	Tractor	MF6290	kg	6420.0	1.0	0.33	138.1	16000	18
Ditching	Machine	Ditch	kg	125.0	1.0	0.33	148.5	2000	3
Ditching	Fuel	Diesel	l	4.0	1.0	.	47.8	.	191
Ditching	Labour	Man	h	1.0	1.0	0.33	.	.	0
Seeding	Tractor	MF399	kg	3317.0	1.0	1.00	138.1	16000	29
Seeding	Machine	Planter	kg	720.0	1.0	1.00	132.9	1500	64
Seeding	Fuel	Diesel	l	8.0	1.0	.	47.8	.	382
Seeding	Labour	Man	h	1.0	1.0	1.00	.	.	0
Seeding	Material	Seed	kg	180.0	1.0	.	13.0	.	2340
Fertiliser spreading	Tractor	MF399	kg	3317.0	2.0	0.33	138.1	16000	19
Fertiliser spreading	Machine	Fspread	kg	520.0	2.0	0.33	127.7	1500	29
Fertiliser spreading	Fuel	Diesel	l	3.0	2.0	.	47.8	.	287
Fertiliser spreading	Labour	Man	h	1.0	2.0	0.33	.	.	0

Fertiliser spreading	Material	N	kg	75.0	2.0	.	78.2	.	11730
Fertiliser spreading	Material	P2O5	kg	100.0	1.0	.	17.5	.	1750
Fertiliser spreading	Material	K2O	kg	0.0	0.0	.	13.8	.	0
Spraying	Tractor	MF399	kg	3317.0	2.0	0.50	138.1	16000	29
Spraying	Machine	Chspread	kg	400.0	2.0	0.50	127.7	1200	43
Spraying	Fuel	Diesel	l	4.0	2.0	.	47.8	.	382
Spraying	Labour	Man	h	1.0	2.0	0.50	.	.	0
Spraying	Material	Herbicide	l	0.1	1.0	.	288.0	.	25
Spraying	Material	Insecticide	l	0.0	0.0	.	237.0	.	0
Spraying	Material	Fungicide	l	0.5	1.0	.	196.0	.	98
Cultivatoring	Tractor	MF399	kg	3317.0	0.0	0.00	138.1	16000	0
Cultivatoring	Machine	field	kg	320.0	0.0	0.00	139.8	2000	0
Cultivatoring	Fuel	Diesel	l	8.0	0.0	.	47.8	.	0
Cultivatoring	Labour	Man	h	1.0	0.0	0.00	.	.	0
Harvesting	Machine	Com. jd955	kg	6000.0	1.0	1.80	116.4	3000	419
Harvesting	Fuel	Diesel	l	27.0	1.0	.	47.8	.	1291
Harvesting	Labour	Man	h	1.0	1.0	1.80	.	.	0
Straw baling	Tractor	MF399	kg	3317.0	1.0	2.00	138.1	16000	57
Straw baling	Machine	Baler	kg	1560.0	1.0	2.00	129.4	2500	161
Straw baling	Fuel	Diesel	l	16.0	1.0	.	47.8	.	765
Straw baling	Labour	Man	h	1.0	1.0	2.00	.	.	0
Transport yield	Machine	Truck	kg	13000.0	1.0	0.50	138.1	12000	75
Transport yield	Fuel	Diesel	l	4.4	1.0	.	47.8	.	210
Transport yield	Labour	Man	h	1.0	1.0	0.50	.	.	0
Transport straw	Machine	Trailer	kg	18000.0	1.0	1.70	138.1	12000	352
Transport straw	Fuel	Diesel	l	4.6	1.0	.	47.8	.	220
Transport straw	Labour	Man	h	6.0	1.0	1.50	.	.	0
Irrigating	Material	Water	m3	1800.0	5.0	.	0.6	.	5670
Irrigating	Labour	Man	h	1.0	5.0	2.00	.	.	0

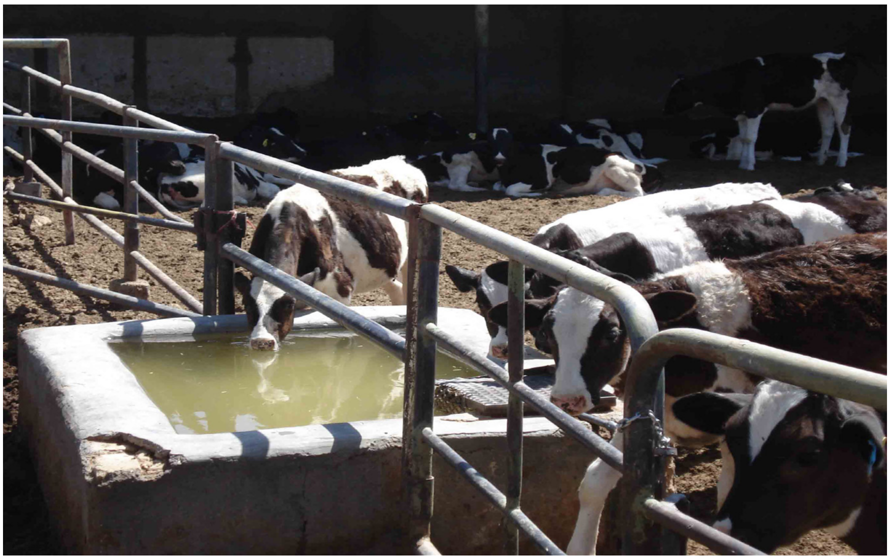
Annex 6. Some pictures from common dairy farms in Iran

An industrial dairy barn

A dairy barn yard

Maize silage silo in a dairy farm in Iran


Manual feeding in a dairy farm


Free water delivery in a dairy farm


Dairy barn yard with roofed area

Declaration

Herewith I confirm that all sections of this dissertation are written by myself, with help and utilisation but independent of the specified references and literatures.

Berlin, 28.06.2013

Mohammadali Maysami