Energy reduction options for the domestic maintenance of textiles

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Preface

This report is the result of research carried out as part of the project '(Evaluation of) Options for Reduction of Greenhouse Gas Emissions by Changes in Household Consumption Patterns', termed 'GreenHouse'. Several research groups collaborate in this project: the Centre of Energy and Environmental Studies of the University of Groningen (IVEM-RUG, the co-ordinating institute) the Department of Science, Technology and Society of Utrecht University (STS-UU) and the Department of Household and Consumer Studies of the Wageningen Agricultural University (HCS-WAU). The research is supported partly by the Dutch National Research Programme Global Air Pollution and Climate Change, phase 2 (1995-2000).

In the preceding projects the feasibility of the methods used in GreenHouse has been established, and the energy requirement and energy intensity of a great many goods and services have been calculated (for past, present and future).

The GreenHouse project aims at analysing household activities in the categories food, clothing, domestic decoration and leisure in order to evaluate the GHG emission reduction potential of substitution of resources, not only within the household realm, but also due to changes in structure of and processes in the economy.

Inter-country comparison is an explicit goal of the project, so comments and suggestions concerning this topic are most welcome.

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1 INTRODUCTION

Household energy consumption exists of direct energy requirement (through energy carriers such as electricity, petrol and gas) as well as indirect energy requirement (energy embodied in products and services). The share of both is approximately a half. This energy is mainly generated by the combustion of fossil fuels, which leads to the emission of greenhouse gasses. These gasses lead to an enhancement of the greenhouse effect, which in turn will lead to global and regional climate changes. Reduction of energy requirement is therefore important. One of the areas where households can reduce their energy use is within textile care and maintenance, including both direct and indirect energy requirements. This can be done by technical as well as behavioural changes.

In this document energy reduction options for the domestic cleaning of textile are discussed and quantified. The goal is to describe reduction options that can be applied by consumers. Only options are taken into account, which are feasible for Dutch consumers nowadays. Technical options not available on the market yet for consumers are excluded from the analysis, such as heat-pump driers and otherwise further improved machines or washing methods.

As said, in the document are taken into account the reduction options regarding direct energy as well as indirect energy. See for more information about indirect and direct energy requirements (Biesiot & Moll, 1995; Vringer & Blok, 1995). For washing and drying the total energy requirement concerns the direct energy use for using appliances, the indirect energy use for the manufacturing for appliances, as well as the indirect energy use for detergents and different textile materials. The total energy requirement for textile care takes approximately 10% of the total energy requirement of a household. Although this is not such a large category compared to e.g. food, a case study about this activity category in households can give a lot of information about the interaction between direct and indirect energy requirement, as well as the interaction between energy requirement and differences in activities of households.

The analyses are done on a detailed level. On a detailed level interaction between the direct and indirect energy requirement is expected. This will influence the result on higher levels, but will not be visible when averaged figures on less detailed levels are used. Also it is tried to incorporate the users' and use situation influences - as opposed to using just technical data. Such users' data is useful and especially available on a detailed level.

First a description and quantification are given of the average primary energy requirement needed to wash and dry one kilogram cotton textile (chapter 2). This is done as a standardised unit is necessary and cotton is the most used material.
In chapter 3 the annual energy requirement for washing and drying per person and per household are quantified. In this chapter the users' situation is taken into account.
Next (chapter 4) the relevant, rather technical energy reduction options for washing and drying are described and the potential savings are calculated. Chapters 5 and 6 reflect on another five

reduction options such as changes in textile materials and different use of appliances. The study ends with chapters 7 (Discussion) and 8 (Conclusions).

2 THE AVERAGE ENERGY REQUIREMENT FOR THE LAUNDERING OF COTTON TEXTILES

The unit for which the average primary energy requirement to wash and dry at home is calculated for, is one kilogram cotton textile. Cotton is the most used material, cotton wash and dry programs likewise. A standard unit is necessary for comparison of reduction options and to further refine the influence of the use situation (chapter 3). In the following first the energy for washing is calculated, than for drying. The calculations start, when possible, with market best conditions, than are refined with average use conditions. For drying, effects for heating/ventilation of the house are taken into account as well.

Washing

To calculate the energy requirement for *washing* one kilogram of cotton textile for a household under average conditions, the direct primary energy requirement for the market-best washing machines at the Dutch market at 1999 are taken as a starting point. These washing machines require 0.95 kWh or 8.55 MJ primary energy for washing 5 kg cotton with a 60°C cotton programme (Miele brochure, 1999). This is 1.7 MJ/kg.

To estimate the average direct energy requirement for washing with an average machine the following assumptions concerning a. the difference between market best and stock, b. the average washing temperature, c. the average load are made:

a. In 1995 market-best washing machines require per cycle about 80% of the energy needed for washing machines in the stock (Kemna *et al*., 1995). For 1999 the same efficiency difference between the market-best washing machines and the stock is assumed.
b. The average washing temperature is about 50°C (van Dijk and Siderius, 1992; Uitdenbogerd, 1998). To calculate the energy use for cycles at this temperature, the relation between the energy use and the washing temperature of 60°C and 40°C of 1:0.54 is taken as basis (Luiken *et al*., 1994). As the average temperature is about 50°C, it is assumed that the energy use is a factor 0.75 of the energy use of a 60°C cycle (also following GEA, 1995, p.24).
c. The average load is about 3.5 kg (van Dijk and Siderius, 1992; Groot-Marcus and Scherhorn, 1994; Uitdenbogerd, 1998), which is only 75% of the average capacity of 4.7 kg (Siderius *et al*., 1995). Assumed is that the energy use of a partly loaded washing machine is as much as a fully loaded washing machine.

When these assumptions are taken into account, the average <u>direct</u> primary energy requirement for washing cotton textile is 2.3 MJ/kg (see next page).

$$E_{kg} = SEC_c * c : mb * t_f / a_w = (0.95 * 9 : 0.8 * 0.75) / 3.5 = 2.3 \text{ MJ/kg}$$

E_{kg} : primary energy use per kg laundry
SEC_c : average energy use in kWh of standardised cycles (60°C, cotton, 4.5 kg)
c : electricity conversion to primary energy (1 kWh = 3.6: 0.4[a] = 9 MJ)
mb : factor of energy use between market best and average machines (0.8)
t_f : factor between the energy use of a 60°C and a 50°C cycle (.75)
a_w : the average (user) weight of a wash load in kg (3.5 kg)

The indirect energy requirement is 1.7 MJ/kg of which 0.7 MJ/kg for the washing machine, 0.1 MJ/kg for water and 0.9 MJ/kg for detergents (Potting *et al*., 1995).

The direct and indirect energy requirements amount to an average total of 4 MJ/kg for washing cotton textiles.

Drying

To calculate the energy requirement for *drying* one kilogram cotton textile for a household under average conditions, the direct primary energy requirement of an average tumble drier is taken as a starting point.

An average condensation drier in stock requires 3.7 kWh per cycle (average load of 5 kg and a rest humidity of 70%) and an air vented drier 2.87 kWh (Test Aankoop, 1992).

As with washing, it can not be assumed that Miele driers are market best with regard to energy use. A condensation drier uses about 3.5 kWh (5 kg cotton, 70% humidity, Miele brochure, 1999), which is about 5-6% lower than in stock. The air vented tumble driers use even more than the driers in stock: 3.3 kWh (5 kg cotton, 70% humidity, Miele brochure, 1999).

To estimate the average direct primary energy requirement for drying with an average machine the following 4 assumptions about the household conditions are made. The assumptions concern a. the rest humidity of the wash load, b. weight of the load, c. ventilation needed for air-vented tumble driers, and d. the loss of warmth of condensation tumble driers. These assumptions are:

a. As said, recent Miele driers use about 3.5 kWh for a condensation drier and 3.3 kWh for an air vented drier per 5 kg cotton if spin-dried up to 70% humidity[b]. If the humidity after

[a] Assumed is that the efficiency of electricity generation in the Netherlands is 40%.
[b] The rest humidity is the amount of water in the textile given as a percentage of the dry weighted textile. A rest humidity of 70% implies that 1 kg textile contains 0.7 kg water.

spin-drying is only 50%, the electricity consumption for drying lowers with 26% to respectively 2.6 kWh and 2.45 kWh (Miele brochure, 1999). Theoretically argued: if half of the loads are spin-dried to a rest humidity of 50% (van Dijk and Siderius, 1992), an average rest humidity of 60% and a reduction of 13% for the average direct energy requirement for 4.7 kg load is assumable (Siderius *et al*., 1995).
The Dutch average spin capacity is 1100 rpm or 57% rest humidity (based on GEA, I, 10, p.13). Thus in practise the available spin speeds already cause a rest humidity of below 60%. For the market best condensation tumble driers is assumed that drying 5 kg cotton costs 3 kWh per cycle and air vented 2.9 kWh per cycle. For the average tumble drier in stock also an efficiency of 13% is assumed.

b. According to (Uitdenbogerd, 1998) the average load for driers is 3.3 kg, only 70% of the average capacity of 4.7 kg (dry). According to GEA (1995, p.16) the average load in Europe is 2.9 kg.

With partly loaded cycles the heated air can bypass the textile and leave the drum without contributing to the drying process (Shepard *et al*., 1990). Another cause for efficiency loss is the fact that the parts of the drier itself need to be heated, which needs a fixed amount of energy (AEG, 1999). This can be assumed to be 35% of the energy needed for a fully loaded tumble dried cycle. The loss of efficiency related to the weight of the load will differ only slightly for condensation tumble driers and air-vented tumble driers. The following Table (1) gives information about the relative energy use for a fully loaded cotton tumble dried cycle in comparison with lower loaded cycles.

Table 1 Energy consumption for fully and partly loaded cycles

Load [kg]	Load [%] of 5.0 kg	Energy consumption in comparison to a 5.0 kg load
5.0	100%	100%
4.5	90%	92%
3.3	66%	72%
0.0	0%	35%

(AEG, 1999)

Apparently a load with 4.5 kg is even a little more energy sound than a full load. For a 3.3 kg load the energy efficiency loss is 6%, increasing to up to 35-38% when no load is dried (see also GEA, 1995, p.56). From the figures in Table 1 can be derived that 2.5 kg loads will lead to an efficiency loss of ± 12%, with 1.25 kg loads more than 25%. Up to a certain weight it still could be interesting to load the tumble drier with less load, as it saves an absolute amount of energy. From one article (100-500 grams) to a weight of approximately 2.5 kg the drying costs relatively a lot of energy. Assumed is that the average weight of the load is 3.3 kg and the energy consumption 72% of a full load for both condensation and air vented driers.

c. The ventilation air of air-vented tumble driers (70% of the stock; Weegink, 1996) is exhausted outside of the house. Consequently, fresh air has to enter the house, which has to be heated to room temperature. The averaged yearly temperature outside is 9.3°C (CBS, 1996), the average room temperature 20°C. The heating of air with rH of 65% takes 1.39 kJ/m³.K (Binas, 1977). On average 225 m³ air (2-3m^3/min * 80-150min) is needed for a cycle of 1.5 hours (Kutch *et al*., 1997; Hloch, 1989).
The primary energy requirement of an air vented tumble drier in stock is 2.87 kWh * 9 = 25.8 MJ/cycle (not yet taken into account the consequences for ventilation).

This means in total:

$$E = E_c + E_v = E_c + (A_a * c * \Delta T) = 25.8 + 3.3 = 29.1 \text{ MJ/cycle}$$

E : Total energy use for a cotton tumble dried cycle (5kg, 70% rH, taking into account ventilation)
E_v : Energy use for heating the ventilated air
E_c : Energy use for air-vented drier - cotton program (25.8 MJ/cycle)
A_a : Amount of air for air vented drier - cotton program (225 m^3)
C : Specific heat of air (65% rH) at constant pressure (1.39 kJ.m^{-3}.K^{-1})
ΔT : Difference in room temperature and temperature outside (10.7°C)

Of the total energy use of 29.1 MJ/cycle almost 11% is needed for the heating of the environment to room-temperature. Approximately 1 MJ/kg laundry is needed for ventilation.

For comparison: according to GEA (1995, p.56) is the energy loss of 'air out' 21.4% of the total electricity use of a cycle (air vented, 4.5 kg). This comes down to 6.2 MJ/cycle primary energy (GEA, 1995, p.56). The energy needed to heat the same amount of incoming ventilation air by gas is lower thanks to the higher efficiency of the heating system, so the extra primary energy needed as calculated (magnitude of approximately 3 MJ/cycle) is acceptable in magnitude and proportion.

Summarising, the energy requirement for a ventilation drier for *use conditions* (3.3 kg or 72% efficiency; 60% rH or 13% reduction; including ventilation energy) is:

$$E_v = E_a * e_w * s_f = 29.1 * .72 * .87 = 18.2 \text{ MJ/cycle}$$

E_v : Energy requirement for air vented driers in daily circumstances (MJ/cycle)
E_a : Energy use for an air vented drier in stock for a standardised load including ventilation energy (29.1 MJ/cycle)
e_w : Energy efficiency for a 3.3 kg load in stead of a standardised 5 kg load (.72)
s_f : Energy efficiency for spin-drying up to 60% rest humidity in stead of 70% (.87)

Note that this is 5.5 MJ/kg. Assumed is thus that the energy needed for ventilation diminishes equally with the energy consumption for the drying itself for lower loads and higher spin capacity.

d. A condenser tumble drier condenses water by cool air (cooling air) or water. The vented process air (the air used for drying the textile, not the cooling air) still has a temperature of 60-70°C (Hloch, 1989), with 100% rH. According to AEG (AEG, 1999) theoretically 100% of the process air is re-circulated, but in reality there is a leakage of approximately 5% for better appliances (AEG, Miele etc.; AEG, 1999) and 10% of the air flow for driers with less quality. It can be assumed that approximately 92% of the process air is re-circulated. The rest of the process air contributes to an increasing humidity as well as an increasing temperature in the house. First the humidity will be dealt with.

   To calculate the so-called condensation efficiency from the escaping process air is difficult for several reasons. First the evaluation of the leakage is difficult because of the dynamic circumstances. Secondly, the humidity of the process air is not constant during the drying process. It is therefore better to look at condensation efficiency as described in IEC 61121 (AEG, 1999). Better driers have a condensation efficiency of 85% to 90%. Normal driers have a condensation efficiency between 75% and 80% and the worst driers only 50%. A 5 kg load with an initial moisture content of 70%, a final moisture content of 0% and a condensation efficiency of 80% leads to 700 g water in the house.

   As said, the escaping process air (8%, 60-70°C) increases the ambient temperature. Contribution to heating of the environment by the leaked process air is 225 m^3*.08*270 kJ/m^3 air (Kutch, 1997) = 4.9 MJ, which is almost 15% of the total energy requirement for average drying (3.7 kWh or 33.3 MJ).
   Also escaping cooling air attributes to a rise in the ambient temperature. There is practically no leakage between the cooling air and process air. Therefore, the cooling air is only heated by the process air in the heat exchanger. The absolute humidity of the escaping cooling air is the same as the incoming air. The temperature of the escaping cooling air is around 45°C. The air flow for cooling air is 4 m^3/minute, the air volume for a tumble dried cycle thus 360 m^3. This air is heated with 25°C from 20°C to 45°C. This would come down to 11.6 MJ (1 kJ/kg.K * 465 kg * 25 K = 11.6 MJ).

   In total almost 16.5 MJ ends up in the ambient air, which is 49% of the total energy requirement for average drying (33.3 MJ). The loss of this energy however, contributes to the heating of the air in the house. This 16.5 MJ primary energy (based on electricity) is 6.6 MJ secondary energy (16.5 * 0.4 efficiency of electricity generation). Divided by the efficiency of the central heating system (approximately 97%) the amount of energy saved by saving natural gas for the heating of the house is 6.8 MJ. This of course is only the case during the winter, half a year. Therefore, a tumble dried cycle by a condensation drier would cost on average 29.9 MJ/cycle (33.3 - 6.8/2).

The energy requirement of a condensation drier is:

$$E_v \quad = (E_a - v_E) * e_w * s_f = (33.3 - 3.4) * .72 *.87 = 18.7 \text{ MJ/cycle}$$

E_v : Energy requirement for condensation driers in daily circumstances (MJ/cycle)
E_a : Energy use for a condensation drier in stock, standardised load (3.7 kWh/cycle)
e_w : Energy efficiency for a 3.3 kg load in stead of a standardised 5 kg load (.72)
s_f : Energy efficiency for spin-drying up to 60% rest humidity in stead of 70% (.87)
v_E : The energy saved for heating ambient air in the winter (3.4 MJ/cycle)

This is 5.6 MJ/kg.

In this calculation the following assumptions are made:
- the tumble drier is used with the same frequency in summer and winter and with the same weight loads in the different seasons,
- the energy ventilated diminishes equally with the energy consumption for the drying itself for lower loads and higher spin capacity.

For both condenser and air vented tumble driers the following aspects are summarised in Table 2: market best vs. stock, test conditions vs. averaged user conditions such as spin capacity and load weight, and finally energy lost to the environment.

Table 2 Energy requirement of market best vs. stock and air vented vs. condenser tumble driers for test conditions vs. averaged user conditions (spin capacity[1], load weight[2], heat loss to the environment [3,4])

Type	Type	Energy req.	Load	Humidity	Remarks
Market best	Air vented	3.3 kWh	5 kg	70%	Test conditions
Market best	Air vented	2.9 kWh	5 kg	60%	Spin Capacity
Stock	Air vented	2.87 kWh	5 kg	70%	Test conditions
Stock	Air vented	1.8 kWh	3.3 kg	60%	Load + spin
Stock	Air vented	18.2 MJ/cycle	3.3 kg	60%	Load + spin + ventilation
Market best	Condensation	3.5 kWh	5 kg	70%	Test conditions
Market best	Condensation	3.0 kWh	5 kg	60%	Spin capacity
Stock	Condensation	3.7 kWh	5 kg	70%	Test conditions
Stock	Condensation	2.3 kWh	3.3 kg	60%	Load + spin
Stock	Condensation	17.5 MJ/cycle	3.3 kg	60%	Load + spin + lost heat

[1] influence of averaged spin capacity: 13% efficiency, factor .87
[2] influence of average load weight: 28% efficiency, factor .72
[3] influence of extra energy needed for ventilation air (+ 3.3 MJ/cycle)
[4] influence of less energy needed for heating (- 3.4 MJ/cycle)

The market share (in stock) of air vented tumble driers is 70%, whereas condensation driers have a share of 30%. Assuming that both drier types are used in the same way, the average domestic energy use for tumble drying is 18.7 * .3 + 18.2 * .7 = 18.35 MJ/cycle or 5.56 MJ/kg, whereby this domestic energy use includes the users' behaviour and the use situation.

The average domestic direct energy requirement to dry a kilogram of cotton at 60% rest humidity, is 5.6 MJ/kg. For the production of the drier itself 0.7 MJ/kg laundry is needed (Potting *et al*., 1995). This amounts to the average total primary energy requirement for tumble drying of cotton textile of 6.3 MJ/kg.

Summary energy requirement for washing and drying 1 kg cotton textiles

The total average primary energy requirement for washing and drying one kilogram cotton at home is 10.3 MJ/kg of which 7.9 MJ direct and 2.4 MJ indirect.

Table 3 The average energy requirement for washing* and tumble drying** one kilogram cotton textile at home taking into account users' behaviour and the use situation

	Energy requirement [MJ/kg]
Washing cotton textile	
Direct energy	2.3
Washing machine (indirect e.r.)	0.7
Water (indirect e.r)	0.1
Detergents (indirect e.r)	0.9
Total washing	4.0
Drying cotton textile	
Direct energy	5.6
Drier (indirect e.r)	0.7
Total drying	6.3
Total average energy requirement	10.3

* 50°C, 3.5 kg
** 3.3 kg, 60% rH, ± energy of the environment

3 THE ANNUAL ENERGY REQUIREMENT FOR WASHING AND DRYING PER PERSON AND PER HOUSEHOLD

As reduction options (described in chapters 4, 5 and 6) often are on household level, practices on household level and related energy requirement needs to be known. In order to calculate the annual energy requirement for washing and drying per household, first the annual amount of washed and dried textile per household is calculated.

Amount of laundry and frequency of washing

Households of different sizes do not have equal amounts of laundry per person. A two-person household washes 4.1 kg per person per week. Three- and more-person households have more laundry; 5.1 kg per person per week (Groot-Marcus and Scherhorn, 1994). The differences are mostly in the amount of household textiles, probably caused by more activity within the household that in turn requires more household keeping as well. This reversed economy of scale will be illustrated in the following.

Different references have a variety in figures as well. The following Table (4) shows the available references and research results. Only one study has been done on one person households and one on 2 person households.

Table 4 Wash loads (wl in kg), the wash frequency (f) and the weight of the loads per load [kg] in relation to the number of persons (p) per household (h)

	Hloch (1989)	Scherhorn (1991, 1992)			Siderius (1992)	GM & S[3] (1994)		GEA (1995)	GM & M[4] (1996)
Wash loads[1]									
wl/p/w [kg]	3.8					4.1	5.1		4.6[2]
wl/p/y [kg]	198					213	265		237[2]
wl/h/y [kg]	198				855	452	1184	718	687[2]
Wash frequency[1]									
F/h/w	1.2	4	7.5	8	4.7	3.0	6.9	4.6	4.4
F/h/y	62	208	390	416	244	156	359	239	229
Weight of loads									
wl/load[1] [kg]	3.2	-	-	-	3.5	2.9	3.3	3	3[2]
p/h	1	3	4.3	4 – 5	-	2	3 – 5	-	2.9

[1] wash load (wl), wash frequency (f), person (p), household (h), week (w), year (y)
[2] derived figures from Groot-Marcus & Scherhorn (1994) and Groot-Marcus & van Moll (1996)
[3] Groot-Marcus and Scherhorn (1994)
[4] Groot-Marcus and van Moll (1996)

From this table the following graph is made (Figure 1), expressing the relation between the number of household members and the absolute amount of laundry in kg/hh.y.

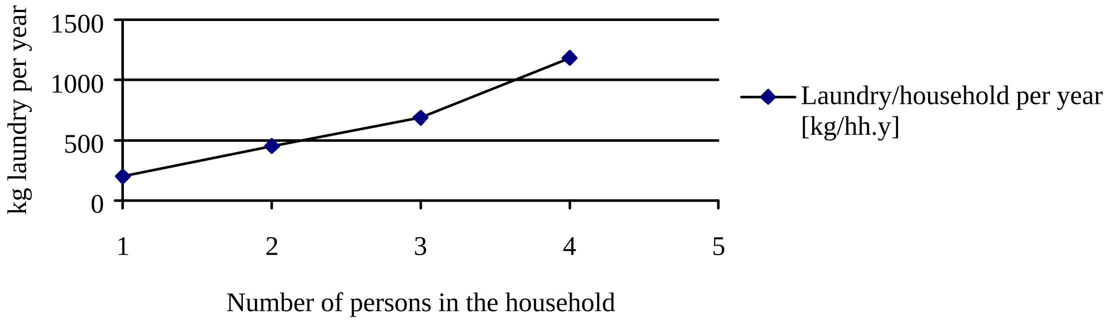

Figure 1 Amount of laundry per household per year in relation to the number of household members (Hloch *et al*., 1989; Groot-Marcus & Scherhorn, 1994; Groot-Marcus & van Moll, 1996)

When a power line is drawn, ($y=192.72x^{1.2479}$; R^2=.989) and is used to calculate with, then an average household of 2.34 persons has 557 kg laundry per year, approximately 238 kg per person per year. The average household size in Netherlands is 2.34.

Note that the amount of laundry for a one person household in Figure 1 is based on a German study. About 42% inhabitants in the Netherlands live in one or two person households (CBS, 1997). Calculated differently, the average annual amount of laundry per person is 243 kg, assuming that one-person households in the Netherlands have relatively as much laundry as two-person households. Different routes of calculations apparently give a difference of ± 2%, which is a minor difference when expressing energy requirement in magnitudes of GJs.

In Table 4 can be seen that the sources give more figures about washing frequency than about amount of laundry per person. The washing frequency increases slowly with the number of persons in the household (see Figure 2).

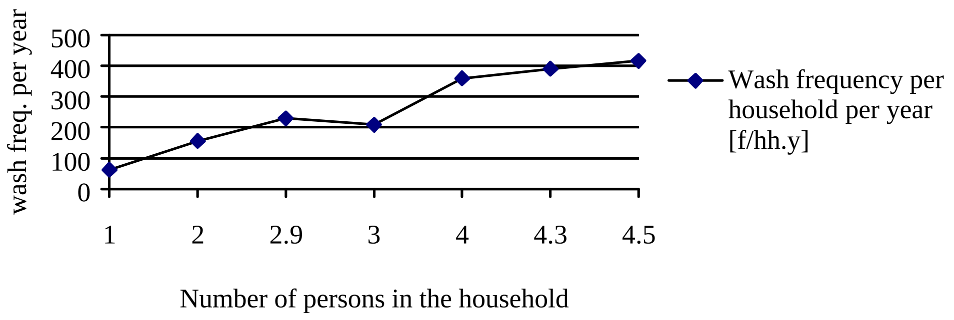

Figure 2 Washing frequency per household per year in relation to the number of household members (Hloch *et al*., 1989; Scherhorn, 1992; Groot-Marcus & Scherhorn, 1994; Groot-Marcus & van Moll, 1996)

The slope of the line in Figure 1 increases with increasing number of persons per household, whereas the slope of the line in Figure 2 decreases with increasing number of persons per household. When Figures 1 and 2 are compared it seems that with more persons per household the washing machines are loaded more fully. In one of the studies this was also found (Groot-Marcus & Scherhorn, 1994). When the household size increases the amount of laundry per year in kilos increases more than the washing frequency. For environmental reasons this is better than the other way around!

The average washing frequency for an average household size of 2.34 persons is 186 for 3 kg loads, 169 for 3.3 kg and 159 for 3.5 kg loads.

Energy requirement per person and per household for washing and drying

In terms of energy requirement for an average household of 2.34 persons: the energy requirement per kilogram cotton laundry was 4 MJ. The annual average energy requirement per person is than approximately 1 GJ for washing, or 2.3 GJ/hh.y, assuming that most of the laundry is made of cotton.

In 1995 about 50% of the Dutch households possessed a tumble drier (Weegink, 1996). Each household with a drier used it 3.1 times a week (Siderius *et al*., 1995) with an average load of 3.3 kg (Uitdenbogerd, 1998). Taking into account the penetration rate of tumble driers and that a household has on average 2.34 household members (CBS, 1997), the annual amount ‘tumble-dried’ laundry per person is 114 kg, or 267 kg/hh.y. As the average energy requirement for a kilo tumble dried laundry is 6.3 MJ/kg, the annual average energy requirement for drying per person is than 0.72 GJ.

As 243 kg/person per year laundry is washed, and 114 kg/person per year is dried, on average 129 kg/person per year is line dried.
Households that posses a drier approximately tumble dry 220 kg per person.year, and more than 20 kg per person is line dried. Although not all the washed laundry is tumble dried, it can be assumed that almost every wash cycle (159; 3.5 kg) is followed by a tumble drying cycle (155; 3.3 kg) with a re-sorted load.

The maximal energy requirement for washing + drying can be calculated when is assumed that all the laundry would be dried in tumble driers. Assuming that every cycle in a washing machine (159 cycles/hh.y, 243 kg/p.y, 2.34 p/hh, 4 MJ/kg, 2.3 GJ/hh.y) is followed by a cycle in a tumble drier (6.3 MJ/kg laundry, 3.6 GJ/hh.y) this would be 5.9 GJ/hh.y.

4 ENERGY REDUCTION OPTIONS FOR WASHING AND DRYING

Energy reducing alternatives for washing and drying are mentioned shortly by Potting and Blok (forthcoming). The ones that will be described and calculated in this chapter, are: improved efficiency of washing and drying, contracting out the laundry, sharing machines and improving the users' intensity, lifetime extension and alternative ways of washing and drying. Also shifts in materials in relation to energy requirement for laundering are taken into account as well as the timing of drying. All these options are applicable by households at present. Other options are described in chapters 5 and 6. Each alternative will be discussed and if applicable the energy reduction will be calculated.

Improved efficiency of washing

The energy reduction options by improving the energy efficiency of washing are discussed here. The options are:

- a higher average load,
- a smaller washing machine,
- using the most efficient washing machine,
- washing with a lower temperature by using detergents with enzymes,
- using a hot-fill washing machine.

A *higher average load* will improve the energy efficiency of washing. The average load as reported by households themselves, lies between 3.7 and 4.3 kg per load (van Dijk and Siderius, 1992) (Groot-Marcus and van Moll, 1996). More accurate and quantitatively measured figures of 2.8 to 3.2 kg/load are published by Groot-Marcus and Scherhorn (1994), see also Table 4. As mentioned in the previous chapter, for further calculations an average load of 3.5 kg is assumed.

- Washing only with full loads (4.5 kg) instead of the average load (3.5 kg) will result in a reduction for the total (direct + indirect) energy requirement for washing by 13% (0.5 MJ/kg).

The indirect energy for a *smaller 3 kg washing machine* is probably as much as for a 5 kg machine. Assumed is that the 3 kg washing machine is filled with 3 kg laundry. For a 90° wash cycle (no pre-wash) the energy-use is ((16.2-11.7)/16.2) = 28% lower (EnergieNed, 1994: 16.2 MJ for a 5 kg washing machine at 90°C, 5 kg load; 11.7 MJ for a 3 kg washing machine at 90°C, 3 kg load).
Provided that this relation is also valid for the other wash programs at lower temperatures, the direct energy requirement for a 3 kg washing machine per kilo laundry washed at 50°C is: 8 MJ/cycle * .72 / 3 kg = 1.9 MJ/kg instead of 2.3 MJ/kg laundry for a normal size washing-machine loaded with 3.5 kg.

- A smaller washing machine can save 10% per kilo laundry compared to 4 MJ/kg direct + indirect energy requirement, under the assumption that it is fully loaded, and in comparison with a not fully loaded normal washing machine.

- The *most efficient washing machines* at the market require 20% less energy than the washing machines in the stock (Kemna *et al*., 1995). This is a reduction of 12% of the total energy requirement for washing (0.5 MJ/kg). Most washing machines will reach an age of 10-12 years. The average energy efficiency improvement is approximately 1% per year.

Most of the energy used for washing (80-90%) is used for heating. For an average cotton load of 4,5 kg 60°C this is: water 63%, heating of the load 7% and heat loss 16%. The rest (14%) is for mechanical action (Miele, w.y; Ybema *et al*., 1995; GEA, 1995). With enzymatic detergents *lower washing temperatures* can be used. The optimal temperature for enzymes is around 40°C. The energy intensity of commercially suitable enzymes is somewhere between 50 and 150 GJ/ton (Genecor, 1998; Ruttloff *et al*., 1979). Assumed is that 1.5% enzymes is used per kilo detergent. With a recommended dosage of 70 gram of detergent (7 MJ; 100 MJ/kg detergent; with ± 1.5% enzymes), the use of enzymes accounts for 0.7% of the energy requirement for an average wash cycle (electricity + detergent). The use of the detergent itself however contributes to about 20 to 50% to the energy requirement of a wash cycle (electricity + detergent) and this percentage is of course higher for lower temperatures.

In the industry is expected that the developments in enzymes eventually can lead to enzymes that work optimally at 8°C. However, a reduction to 40°C seems more likely as the time needed for a cycle is comparable to what it is now. Such a time span is acceptable for households and therefore the industry aims at developments towards 40°C (Ybema *et al*., 1995; Ribhagen, 1997). The energy intensities of enzymes differ with a factor 30, depending on the state of genetic modification of the bacteria and fungi that produce enzymes and on the process control. The energy intensity of commercially suitable enzymes is somewhere between 50 and 150 GJ/ton (Genecor, 1998; Ruttloff *et al*., 1979). Enzymes in compact heavy duty detergents account for 1%, in compact colour detergents for 2% and in liquid heavy duty detergents for 3% (Terpstra, 1997; Ribhagen, 1997, Uitdenbogerd, 1997). Not only lower temperatures are the result of using enzymes. With the use of lipases for example, the amount of surfactants (energy intensity around 63 GJ/ton) can be lowered with 10-20% (Ribhagen, 1997). As a consequence, less surfactants lead to smaller and less packaging, less transport costs and thus to a lower indirect energy requirement to wash a kilo laundry. In recent years these developments in the industry took place already. Now the consumer needs to follow these trends and should wash more often at

The distribution over wash temperatures and the energy requirement per cycle in the Netherlands are according to GEA (1995) as follows:

- 57% at 30-40°C - 4.9 MJ/cycle cotton
- 33% at 50-60°C - 9.8 MJ/cycle cotton
- 10% at 70-90°C - 17.5 MJ/cycle cotton, on average 7.8 MJ/cycle[c].

When the distribution over temperatures changes to lower temperatures such as more at 40°C:

- 80% at 30-40°C - 4.9 MJ/cycle cotton
- 15% at 50-60°C - 9.8 MJ/cycle cotton
- 5% at 70-90°C - 17.5 MJ/cycle cotton, the average direct energy requirement per cycle is 6.3 MJ (1.8 MJ/kg).

This distribution is based on the fact that some heavy stains, like motor-oil and red wine, still best can be washed at temperatures higher than 60°C (Schop, 1998) and undoubtedly some households will not change to lower temperatures for e.g. white cotton laundry despite the dirt level.

- The use of enzymes in detergents can save 20% of the current direct energy requirement for washing (2.3 MJ/kg) in the Netherlands, if a shift in temperatures occurs and when the use of enzymes and new detergent compositions compensate for lower wash temperatures and give the same wash performance. The energy requirement for extra enzymes can be neglected (0.7%).

A *hot fill washing-machine* in combination with a gas-fired warm water supply saves primary energy compared with washing machines which are heated with electricity.
The electricity requirement for the Miele hot-fill machine falls from 1.05 kWh to 0.6 kWh for a 60°C cycle (Miele, 1997a), a reduction of 43%. Earlier is mentioned that the heating of water requires 63% of the total energy requirement for a 60°C cycle. The difference of 20% is probably used for additional heating of the water during the cycle to compensate for heat loss. If the heating-energy of 0.45 kWh electricity (= 4.05 MJ primary energy, based on an electricity efficiency of 40%) has to be provided by a gas-fired warm-water supply with an assumed average efficiency of 55% (Consumentenbond, 1997), this still needs 2.95 MJ primary energy. A cycle then needs 5.4 + 2.95 = 8.35 MJ primary energy, a reduction of 12%.

c In chapter 2 the calculated energy requirement for normal washing machines based on the market best washing machines and taking into account the average wash temperature and weight of the load is 8 MJ/cycle, so the results following different calculation routes are rather consistent.

- A hot fill washing machine thus leads to a reduction of about 14% of the direct primary energy needed for a 60°C cycle (0.5 MJ/kg). However, the saving potential in percentages depends on the washing temperature and the efficiency of the warm water supply.

The smaller saving of 14% in comparison with the 20% saving according to (Kemna *et al*., 1995) is due to the lower assumed efficiency of the gas-fired warm water supply, namely 55% instead of 65%. Besides, when taking the water distribution system throughout the house into account, the efficiency could be even less.

The relative energy saving will also be smaller when the washing temperature lowers.

- As mentioned earlier, about 14% of the energy requirement of a 60°C cycle is used for the motor (GEA, 1995). At 50°C this is 18%.
- A decrease in energy saving is caused due to the hot fill from 14.3% to 13.7% of the *direct* primary energy requirement. For a 50°C cycle the eventual saving is 0.4 MJ/kg laundry, 8% of the *total* primary energy requirement for washing.
- For a 40°C cycle the savings are 0.2 MJ/kg laundry, 5% of the *total* primary energy requirement for washing.

As consumer and industrial trends of washing temperatures are in the direction of 40°C, in future the energy reduction potential of hot fill washing machines will not be a major one.

- Applying the three most important options together (market best, loaded fully, 40°C) = 0.95 kWh $^{(60°C;\ 4.5\ kg)}$ $*$ 9 $*$ .54 $^{(60°C \rightarrow 40°C)}$ / 4.5 kg/load = 1.0 MJ/kg direct energy, the total energy requirement for washing one kilogram cotton textile reduces from 4 MJ to 2.7 MJ, a reduction of 33%.

Improved efficiency of drying

The energy reduction options by improving the energy efficiency of drying are discussed next. The options are:

- a higher average load of tumble driers,
- a lower humidity by better spin-drying,
- using the most efficient drier,
- using a natural gas-fired drier,
- line drying,
- seasonal use of the drier,
- space for line drying more laundry.

A *higher average load* will improve the energy efficiency of drying. The average load for driers is 3.3 kg per load (Uitdenbogerd, 1998). If

- Drying only with full loads instead of average loads, results in an energy requirement reduction for drying with 2% to 6% per cycle (see Table 1, p.4).

Spin-drying at a higher number of revolutions (rotations per minute, rpm) reduces the remaining water in the laundry and the energy requirement of the drier. Most of the new washing machines at the market provide in high spin rates (EnergieNed, 1997). Miele condensation driers require 3.5 kWh per 5 kg load (cotton) if the load is spin-dried to a rest humidity of 70% and 2.6 kWh/load if the load is spin-dried to rest humidity of 50%[d]; 26% less (Miele, 1997a). This results in a saving of 1.7 MJ/kg for a full load (4.5 kg). The extra energy requirement for the higher spin rate is negligible (Shephard *et al*., 1990).

- A saving of 1.0 MJ/kg is achieved if spin-dried up to a rest humidity of 50% instead of the average 60% rest humidity. In the Netherlands the average rpm is more than 1100 rpm (GEA, 1995). The rest humidity of cotton that is spin-dried at 1100-1200 rpm is around 60%. It would need a shift to 1300 rpm to achieve a rest humidity of 50% (GEA, I,10,p.13).

> Compared to the rest of Europe (on average 877 rpm) the Netherlands has a relatively high average spin speed. An assumption made in the GEA background report 10 (I, 10, p.13) is that within 50 years the average spin speed will double from 700 to 1400 rpm by 2016 with a result of approximately 25% energy reduction for drying since the 70ties. Following this assumption, without extra measures it would take 14 years for all the Dutch laundry is spinned up to a rest humidity of 50%.

- The *most efficient tumble driers* at the market were in 1995 30% more efficient compared to the stock of 1995 (Kemna *et al*., 1995). However, the market-best machines according to (EnergieNed, 1997) are only 10% more efficient compared with the average energy requirement according to (Potting *et al*., 1995). Assumed is an energy efficiency improvement of 20% (1.1 MJ/kg) for the most efficient driers compared with the stock.

The 'White Knight NL 442' natural *gas-fired drier* uses about 0.1 m^3 gas and 0.05 kWh per dried kilogram of cotton textile with a rest humidity of 70% (Posthuma, 1995). The same applies for a Miele gas-fired drier (Miele brochure, 1999). Gas-fired driers are air-vented tumble driers. The gas-fired drier requires 3.6 MJ/kg for a standardised load, a reduction of 31% compared to an air vented drier in stock for standardised loads (5 kg cotton of 70% rH, 2.87 kWh or 25.8 MJ/cycle). In comparison with condensation driers in stock it saves 46% for standardised loads.

For the domestic situation is assumed that (see also chapter 2):

- the energy saving due to a better spin-drying (from 70% up to 50% rest humidity) is analogue to the electrical driers; 26%,

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[d] To achieve a rest humidity of the laundry of 70% the spinning rate of the washing machine has to be 800 rpm, and to achieve a rest humidity of 50% the spinning rate has to be 1400 rpm (Luiken *et al*., 1994).

- the average domestic load weight (3.3 kg) is the same for gas-fired driers as for normal driers, and that the efficiency for lower loads is equal as well,
- the extra energy need for the ventilation of the air is equal to a normal air-vented tumble drier.

- For the domestic situation, taking into account the users' behaviour and the use situation, the energy requirement for a gas fired drier is than 18 MJ/cycle * .72 $^{(5 \rightarrow 3.3\ kg)}$ *.87 $^{(70\% \rightarrow 60\%\ rH)}$ + 3.3 = 14.6 MJ/cycle or 4.4 MJ/kg. This saves 23% compared to the average drier in stock under users' conditions.

Line drying requires energy because water has to be evaporated. The evaporation value for water is 2.3 MJ per litre. If the washed textile has a rest humidity of 60% and only 50% of all the laundry is dried indoors during the heating season, on average 0.7 MJ/kg is necessary for line drying, neglecting the energy requirement if the house has to be ventilated extra[e] and neglecting the energy requirement for the line itself.

- Replacing all the tumble drying by line drying - not taking into account the two mentioned aspects - saves 89%.

The evaporation of moisture cools the environment and the relative humidity rises. Of a small room of 22.5 m^3 (3*3*2.5 m) dry air will decrease 0.001°C in temperature. Humidity rises from 65% to 85% at a ventilation rate of 0.5. Assuming that the energy use for ventilation is the same as for an air vented tumble drier (1 MJ/kg) than the energy requirement for line drying is 0.7 + 1 = 1.7 MJ/kg, and reduction compared to the present drying situation ((6.3 - 1.7)/ 6.3)*100% = 73%.

- With a dry frequency of 155 cycles/hh.y, 1.7 GJ/hh.y is used. If the air-vented drier would be used during *wintertime* only (6 months from October to March, T_w = 7°C; April to September T_s = 11.6°) this would save 203 MJ/household.year for heating of ventilation air (39%) or 4% of the total energy requirement, at the present frequency rate.

As often 'lack of space' is mentioned as an argument for the purchase of a tumble drier (Aarts, 1995), more space seems inevitably connected to the option 'more line drying'. In order to prevent the purchase of a tumble drier, enough and suitable space for line drying laundry could be a promising option.

The VAC (1997) advises 5-6 meter line per person, or for one full load (5 kg) 10-12 meters, with a minimum distance of 0.18 m between the lines. The average household size of 2.4 will thus require 12-14.4 meters. With a length of 1 meter, 12 meters will take 2.3 m². A washing

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[e] Expected is that the energy requirement for heating air for extra ventilation when line drying, will not be larger than the energy requirement for heating ventilation air for (air vented) tumble driers.

machine, or a drier, takes 1.1m² (VAC, 1997). Of this surface is 0.7 m² needed at the front. In total a minimum surface of 3.4 m² is needed for a washing machine and cloth lines.

According the IEC 61121 norm cotton is dry (humidity 8%) after 24 hours line drying at a room air-temperature of 20°C, rH 65% and spin-dried at 1000 rpm. With 4.5 wash cycles a week (drying time 108 hours) the surface is used for 64% of the week.
A dry cycle in a drier takes 1.5 hours. This means that the drier is used for 6.8 hours per week. The drier, the surface and the time are efficiently used for 4%.
The inefficiently used surface is for the options more or less equal, but the lines need more space: 1.2 m² absolute.

- One m² living space costs 0.14 GJ/y (Vringer, 1993). Additional space for just line drying (1.2 m²) therefore costs 168 MJ/y or 0.2 MJ/kg laundry.

The options line drying and extra space together save 82%.

The fact that the space needed for line drying is used for 64% of the week, based on a norm that can be applied inside the house, justifies a special place for line drying and not a space that is used for other purposes as well, like a regularly used stairwell or bedroom. If drying conditions are more humid or at lower temperatures (scullery) or if the rotation speed of the spinning is lower the drying time will increase. Irregular used space in the attic or guest rooms can of course be used for line drying, however this can result in long and inconvenient run lines from the washing machine to the place to dry. Especially in smaller apartments space for line drying should be taken into account.

If the options higher loads, higher spin-drying capacity and gas-fired driers are applied together (excluding more efficient electrical driers), the total energy requirement for drying one kilogram cotton textile with an air vented tumble drier reduces from 5.9 MJ/kg to 2.7 MJ/kg (54%). For condensation driers this saves 49%, and on average 53%.

By applying the most efficient machines in the most efficient way the total energy requirement for washing and tumble drying can be reduced from 10.3 to 5.4 MJ/kg; a total reduction of 48%.

5 DIFFERENT USE OF TEXTILE MATERIALS

In this chapter the effects on energy requirement for washing/drying and room heating when different textile materials are used will be discussed. The different use of materials include more use of wool and replacement of cotton by polyester/cotton. Wool or other insulating (synthetic) textiles can possibly have consequences for room heating, and both wool and synthetics have consequences for laundering as well.

Wool

By adding clothing, a lower indoor temperature could be more acceptable, especially when more woollen clothing is used. It can be assumed that extra (woollen) clothing can compensate for 1-2°C heating (based on McIntyre & Griffiths, 1975). During the period 1986 - 1991 the average indoor temperature increased with 1°C (Weegink, 1994) from 17.3 to 18.2°C. Thanks to improved efficiency measures for heating in dwellings the amount of gas used per households decreased whereas the total amount of gas used in the Netherlands has not changed due to the increasing number of dwellings. The outside air temperature in wintertime is 7°C, therefore during 7 months (the heating season is from the 1st of October to the 1st of May indoor temperature must be risen with 11.2°C. This takes 53.7 GJ/hh.y, derived from the average amount of gas (1678 m^3, 32 MJ/m^3 (Weegink, 1994)) that is used for heating.

- Heating 1°C less could theoretically save 4.8 GJ/hh.y (9%). For each of the 2.4 household members 3 (woollen) sweaters/jumpers, 3 under shirts, 3 cotton blouses, 3 pairs of socks and 2 indoor trousers can be purchased extra, so that one can choose to either wear an extra blouse, under shirt or sweater during the day and in the evenings extra socks or a warm indoor trouser. This would cost (with a life time of 3 years) 2.6 GJ/hh.y of indirect energy (e.g. 1 man’s jumper 342 MJ/piece; de Paauw & Perrels, 1993) and 0.3 GJ/hh.y for washing (increase in washing frequency of 0.6 per week) for a wearing frequency of 1 set extra per person per week.

Depending thus on the amount of extra clothing needed, reduction of indoor air temperature can be worthwhile.

Wool has consequences for maintenance practices and thus for energy requirement as well. It can be worn longer as the fibres attract less dirt compared to cotton and therefore needs to be washed less frequently; wool needs to be washed at low temperatures and can not be tumble dried. Wool however has a high emission of greenhouse gases (methane) (Potting & Blok, 1995), so synthetic alternatives for wool with high insulation capacities might have a positive reduction potential related to room heating as well.

In 1975 an experiment has been done to test whether it is possible to compensate for low ambient temperatures by adding clothing. The extra clothing consisted of a long sleeved woollen sweater adding 0.3 clo units (one unit of thermal insulation of clothing: 0.155 $W/m^2.°C$) to the insulation of a clothing ensemble. The test has been performed in two chambers of 15°C and 19°C with forty subjects. In both chambers the mean radiant temperature was equal to the air temperature; the air velocity was less than 0.1m/s. The conclusions were that in cool conditions an added woollen sweater over clothes is equivalent to raising the temperature by about 2°C but although the added sweater made people warmer it did not alleviate their discomfort. The feelings of discomfort were apparently associated with cold feet. The conclusions of this experiment therefore were that it is not possible to rely on extra clothing to overcome the effect of low air temperatures and that this is important to bear in mind when discussing energy savings to be made by reducing internal temperature in buildings (McIntyre & Griffiths, 1975). However, this experiment was performed at quite rigid circumstances (15°C). It is possible that because of the higher insulation levels of Dutch houses radiant air temperature of walls, floors and furniture is higher as well and certainly when compared with the test conditions. Therefore setting back the thermostat in Dutch houses could be an act of reducing temperature without negative consequences for comfort caused by low radiant air temperatures. A little bit of extra clothing then can compensate for the lower air temperature. On the other hand the higher insulation levels of the Dutch houses could have led to higher absolute humidity and therefore to the need of higher air temperatures, which can hardly met by extra clothing. Note that a cooler house or a house with better insulation can 'handle' less moisture and therefore more difficulties with line drying and consequently the need for a drier can emerge. Nevertheless it is concluded that wearing a woollen sweater

Synthetic textiles - washing

The energy use to wash and dry synthetic textile differs from the energy use to wash cotton textile. This is due to the differences between the washing and drying programmes and the maximum load (see Table 5). Besides this, synthetic fibres absorb less water than cotton fibres and lower temperatures for washing are required. Both aspects could lead to the formulation of a reduction option such as shift in textile materials. In Table 5 the (relative) energy use and load for synthetics and cotton for standard test situations are ranked for year of publication of the references.

Table 5 Energy use (e.use), load and relative energy use per kilo for washing when comparing standard synthetic (40°C and 60°C) and cotton (60°C) loads

Textile	Direct e.use [kWh/load]	Maximum load [kg]	Relative e.use	Reference
Cotton	1.17	4.7	1	Test Aankoop 1987
Synthetic 60°C	0.93	2.2	1.7	16 washing machines
Cotton	1.29	3.8	1	Test Aankoop 1988
Synthetic 60°C	1.04	1.9	1.6	14 washing machines
Cotton	1.3	4.77	1	Test Aankoop 1992
Synthetic 40°C	0.6	2	1.1	9 washing machines
Cotton	1.3	4.75	1	Luiken *et al*. 1995
Synthetic 60°C	0.9	1.75	1.9	
Cotton	1.1	5	1	Consumentenbond 1996
Synthetic 60°C	0.8	2.25	1.6	6 washing machines
Cotton	1.1	4.8	1	Consumentenbond 1998
Synthetic 60°C	0.75	2.2	1.5	14 washing machines
Cotton	0.95	5	1	Miele brochure 1999
Synthetic 40°C	0.45	2.5	0.9	

If the references for 60°C in Table 5 are taken into account, the relative energy use for washing a kilo synthetic textile at 60°C is about 1.66 times higher than for washing a kilo cotton textile at 60°C. The higher direct energy use per kilo is due to the lower maximum load per cycle. For washing cotton at 60°C and synthetic at 40°C there is almost no difference in energy use (see the third and last row in Table 5).

As can be derived from Table 5, washing a standard load of 2.5 kg synthetic at 40°C costs approximately 0.23 kWh/kg or 2.1 MJ/kg. In fact this includes three reduction options: washing at lower temperatures with market best washing machines and with an optimal load for synthetics.

Including the indirect energy for detergents, water and the washing machine itself, the total energy requirement for washing synthetics is 3.8 MJ/kg.

Synthetic textiles - drying

The average air vented tumble drier in stock uses 0.49 kWh/kg or 4.4 MJ/kg. The average condensation drier in stock uses 0.55 kWh/kg or 5 MJ/kg (Test Aankoop, 1992). The market air vented tumble drier uses 0.46 kWh/kg or 4.1 MJ/kg. The market best condensation drier uses 0.52 kWh/kg or 4.7 MJ/kg (Miele brochure, 1999).

Including the indirect energy requirement for the drier itself, the total energy requirement for drying synthetic textile is at the most 5.7 MJ/kg for condensation driers in stock; 11% lower than for cotton textile (see Table 3, 6.3 MJ/kg). With the market best air vented tumble driers this is 4.8 MJ/kg, 25% lower than for cotton. The lower energy requirement for drying is as expected, because after spin-drying synthetics contain less water. Besides this it is easier to release water from synthetic fibres than from cotton fibres.

Synthetic textiles – washing and drying

The total primary energy requirement for washing at 40°C and drying with an air vented tumble drier, both with the market best appliances, with the synthetic programs and with the advised loads (1.5-2.5 kg), is 3.8 MJ/kg for washing + 4.8 MJ/kg for drying = 8.6 MJ/kg. This is 17% lower compared to the average users' situation (10.3 MJ/kg, Table 3: washing 3.5 kg cotton textiles at 50°C and drying 3.3 kg with average appliances in stock).

For the most unfortunate situation, the condensation drier in stock (5.7 MJ/kg) and washing the synthetics at 60°C with washing machines in stock (3.9 direct MJ/kg + 1.7 indirect MJ/kg) laundering synthetics costs 11.3 MJ/kg. This is 9% more than the averaged users' energy requirement (10.3 MJ/kg).

For comparison the results of these calculations are summarised in Table 6.

The following aspects are relevant to take into account:

- The synthetic washing programme is not used often in the Netherlands in contrast with cotton programmes (van Dijk en Siderius, 1992). Synthetics materials are often applied in blends with cotton, e.g. polyester/cotton blends (PES/CO) 35/65 or 45/55. Probably these blends are treated as cotton laundry.
- Note that the functional units of a kilogram cotton textile and a kilogram synthetic textile differ. Articles (blazers, suit-jackets, pantalons (neat trousers), trousers, jumpers, cardigans, blouses, overalls, skirts and dresses) made of 100% cotton weigh 0.397 kg on average. Articles made of synthetics or semi-synthetics (based on cellulosic fibres) weigh on average 0.371 kg, a difference of approximately 25 gram per article (based on Fenecon, 1994).

Table 6 Energy requirement (e.r.) for washing and drying cotton and synthetic materials [MJ/kg] with and without saving measures[1], in comparison with the present situation for tumble drier owners

	COTTON, Present situation	COTTON, lowest e.r.	SYNTHETICS, lowest e.r.	SYNTHETICS, highest e.r.
Specifications	stock[2] 50°C, cotton	market best 40°C, cotton gas-fired drier[3]	market best 40°C, synthetics air-vented drier[4]	stock 60°C, synthetics condensation drier[4]
Washing direct	2.3	1	2.1	3.9
Indirect	1.7	1.7	1.7	1.7
Total washing	4	2.7	3.8	5.6
Drying direct	5.6	2.7	4.1	5
Indirect	0.7	0.7	0.7	0.7
Total drying	6.3	3.4	4.8	5.7
Total [MJ/kg]	10.3	6.1	8.6	11.3

[1] gas-fired driers and most efficient appliances
[2] for tumble drier owners, 3.5 kg load washing; 3.3 kg drying; 60% rest humidity after spin-drying, share of air-vented driers 70%
[3] full loads for washing and drying, 50% rest humidity after spin-drying
[4] synthetic standard load 2.5 kg, 50% rest humidity after spin-drying

From Table 6 can be concluded that especially washing at 40°C and using a gas fired drier makes a difference. Also can be derived that synthetics make more difference for drying than for washing. No figures are available for the energy requirement of a gas-fired drier for drying synthetic laundry. The combination of washing synthetics as cotton and drying it with a synthetic program with a gas fired drier could be a reduction option as well.

Summarising, wool or materials with the same insulating capacities reduce energy requirement for the heating of houses. The replacement of cotton by synthetic fibres or mixtures of cotton/synthetic fibres does not necessarily reduce the energy requirement for washing when washed at 40°C. It even has a negative effect when washed at 60°C with washing machines in stock. The replacement by synthetic fibres however, has a potential for drying, even with condensation driers in stock.

6 OTHER REDUCTION OPTIONS FOR DOMESTIC LAUNDERING

In this chapter the reduction options, which need other laundering practices and purchase behaviour of appliances, are described. These options are:

- contracting out
- life time extension of appliances
- sharing products and improving users' intensity.

Contracting out

The energy requirement for contracting out the laundry to a launderette is not lower than the energy requirement for washing and drying at home. According to (Potting *et al*., 1995) the energy requirement per kilogram textile washed and dried in a launderette is 15.4 MJ/kg and if washed and dried in an industrial laundrette 13.7 MJ/kg. Compared with washing and drying at home this is 3 to 5 MJ/kg higher, mainly due to the fact that all the laundry that is washed is also tumble dried. The choice between line drying and spin-drying cannot be made if the laundry is contracted out. Because of these two reasons a further energy analysis of this option has not been made here.

Lifetime extension of appliances

Extending the lifetime of the washing machine and drier can reduce the energy requirement for producing and distribution these machines. An average washing machine costs approximately 4.3 GJ to manufacture, including the transport to customers (Ebersperger & Mauch, 1993). In a year and for one household the direct energy is 3-18 times as much as the indirect energy (this study Table 2; Ebersperger, 1993; Uitdenbogerd, 1998), depending on the washing frequency and the assumption of the lifetime of a washing machine. This indicates that extending the lifetime of washing machines does not have much potential, as will be pointed out in the following.

- The average lifetime of washing machines is 13.6 years (van Dijk and Siderius, 1992). The average lifetime reported by the producers of washing machines is 12 years with an average price of Dfl. 1900. Miele is the only brand who reports a lifetime of their machines of 10.000 hours (Miele brochure, 1999) with an average price of Dfl. 2400 (Consumentenbond, 1996). If the price difference is supposed to be equal to the extra energy required for producing the more expensive Miele washing machine, the net reduction of the energy requirement by using the Miele equipment, is 0.2 MJ per kilogram washed textile. If the production of the more expensive Miele washing machines does not require more energy the net energy reduction is about 0.3 MJ per kilogram washed textile (2%). If the same applies for driers, the net energy reduction per kilogram washed and dried cotton is 0.4 to 0.6 MJ/kg; 4 to 6% of the total average energy requirement for washing and drying at home.

- The effects of an extension of the warranty will probably also result in a longer lifetime. What exactly the effects are of an extension of the warranty is not known, but it can be assumed that the reduction will not exceed the reduction that can be achieved by buying Miele washing machines. The warranty of washing machines is often one year, which is far from the average age when defects occur (± 9 years). According to (Schelbergen & Serail, 1987), a defect occurring in an on average 9 years old washing machine will be repaired in 73% of the cases, mainly depending on the expected rest lifetime and the price that a new washing machine will cost. The first factor is related to the expected chance of a new defect within a half year after repairing, the number of defects that already occurred in the past, the spin-drying result of the washing machine and the appearance of the washing machine. It is concluded that the same symptoms of a defect can lead to different perceptions of the seriousness of the defect. This is related to the existing perceived *reliability* of the washing machine and is thus related to the earlier mentioned expected rest life time (Schelbergen & Serail, 1987).

Besides the energy reduction that can be achieved by extending the lifetime of appliances, the development of new technical innovations that reduce the direct energy requirement of appliances can possibly be complicated or delayed. A German study about the optimised lifetime of washing machines taking into account the accumulated direct and indirect energy requirement, revealed no sharp point from which replacing is more energy sound. Replacing between 8 and 20 years made no significant difference (Ebersperger, 1993). In this study is also calculated that the measures to increase lifetime from 10 to 20 years such as a better bearings of drum, motor and pump, better materials and improving the corrosion protection increases the indirect energy requirement with approximately 3%. The study shows that the energy use for the different programs (hot, coloured, fine etc.) decreased during the last 20 years, especially for 90° and 60°C cotton cycles. It also shows that an enhanced shift towards 40°C cycles offers the highest potential for energy saving (Ebersperger, 1993).

Sharing appliances and improving users' intensity

The number of washed cycles during the life time varies from 5000 cycles of 2 hours for Miele washing machines (Miele brochure, 1999) to 2000-3000 for washing machines of average quality. Improving the users' intensity by for example sharing washing machines is therefore not such a sensible reduction option as the life time depends on the frequency of use, unless improving users' intensity means that the machine is used more efficiently with higher loads. Besides, sharing washing machines might need a common space, which will cost extra energy as well (see Chapter 4).

Summarising

From the above-described aspects can be concluded that the energy soundness of a washing machine depends on the number of wash cycles that are done during its lifetime. The total energy requirement depends a little on the quality of the washing machine and mainly on the energy use for each wash cycle, and consequently on temperature choice.

7 DISCUSSION

Some comments have to be made before drawing our conclusions. The comments are separated in general comments, comments related to acceptance of the reduction options and more specifically for washing, drying and textile materials.

General comments

- For the calculation of the average washing and drying of cotton textile, differences are found in several sources. The choice of the sources can influence the final saving potentials. However, the influence of the saving options on the primary energy requirements will be less affected by the choice of the sources.

- The energy requirement for laundering (washing + drying) is compared to the present situation of tumble drier owners expressed in MJ/kg. For washing the averaged figures for owners and non-owners are taken, for drying the averaged figures for tumble drier owners. Thus, differences in laundering practices for non-owners and owners are not taken into account. It is likely that tumble drier owners wash more frequently, whereas of the other parameters are probably not necessarily different. One of the reasons to take averaged figures for washing is that these are the available figures.
  To approach the present use situation still as good as possible, the used figures take into account the use practices of households such as load weight for washing and drying, frequency of washing and drying, temperature of washing and rest humidity after spin-drying.
  However, it would have been more precise when the figures for washing would have split for tumble drier owners and non-owners. Another solution for this unequal comparison is to average the figures for drying as well over owners and non-owners. About 50-60% of the households own a tumble drier. This would mean that the average energy requirement for drying is not 6.3 MJ/kg, but 6.3*.55 = 3.5 MJ/kg, so that the average energy requirement for laundering in total is not 10.3 MJ/kg but 7.5 MJ/kg. In this way no clear comparison could have been made what the consequences would be of more line drying, using a gas-fired drier etc. The reduction potential as a percentage of the energy requirement of the ‘actual situation’ than would depend on the penetration rate of tumble driers (and this rapidly increasing). As the penetration rate for washing machines is almost 100% this problem does not occur with washing. Besides this, when a penetration rate is involved in the calculation, attention is taken away from the use practices influencing the process. Penetration rate will be important when feasibility of reduction options is discussed, not when economical and technical potentials are calculated.

- The indirect energy requirement for water, washing machines, driers and detergents is taken from Potting *et al*., 1995. In Potting *et al*., 1995 is calculated with 600 kg laundry per household per year, life time of 13-14 years, standard washing loads and in MJ/kg laundry as well. Not taken into account in Potting *et al*., 1995 and in this study are the differences in indirect energy requirement when using other loads. Compared to the direct energy required in the laundering process in the users' situation, the indirect energy requirement is approximately a fifth. When is calculated for 3.5 kg in stead of 5 kg loads the indirect energy requirement rises to 3.3 MJ/kg. The share of indirect energy requirement than rises to 29% (8+3.3=11.3). This way of calculating assumes that although loading lower life time does not change. However, there is a relation between loading and frequency of washing. Life time does not depend on load, but on frequency of use, and many other aspects, see chapter 6. ????

Comments on acceptance

- Note that households will accept not all the here-described alternatives. Technical improvements can help households to implement the options, such as build-in balance for an optimal load of the washing machine and drier, a standard hot-water connection on the site of the washing machine, a gas connection on the site of the drier or more space in the house to line-dry the laundry.

- In this document the reduction options are compared for their results on energy requirement. However, attributes related to use can determine the feasibility of reduction options, and consequently the eventual reduction potential. This is investigated in (Uitdenbogerd *et al*., 1998).

- An example of this: a smaller washing machine can save 17% per kilo laundry, under the assumption that it is fully loaded and in comparison with a not fully loaded normal washing machine. In practice the wash load will be lower and at the most 2.5 kilos, which results in 2.3 MJ/kg and saves 0%. The average load is approximately 70% of the capacity, for smaller washing machines this probably will be the same. Therefore, as this 2.5 kg load is a high estimation, the practical result will be an increase in energy requirement per kilo laundry instead of a decrease.

Comments related to washing

- For washing is assumed (p.2) that the energy use of a partly loaded washing machine is as much as a fully loaded washing machine. With the presently build in load automat or fuzzy control a 1 kg load uses more than 40% less and a 2.5 kg load uses 10% less energy compared to a 5 kg load (Miele brochure, 1999). The difference for a 3.5 kg load (present use situation) can be neglected.

- Loading more fully from 3.5 kg to 4.5 / 5 kg is only possible for cotton and linen. For synthetics, wool and fine materials different washing advices exist. Cotton and linen can be washed with a full load at temperatures up to 95°C. Synthetics are advised to be washed in 2.5 kg loads, at 30-60°C, wool and fine in 1 kg loads, cold to 30-40°C, and silk (hand wash) cold to 30°C (Uitdenbogerd *et al*., 1998). The occurrence of materials in the Netherlands combined with washing advices (.57 * 5 kg cotton and linen + .28 * 2.5 kg synthetics + .15 * 1 kg fine (wool + cellulosic) this means an average load of 3.7 kg. The present average load is already 3.5 kg. Based on this a higher efficiency for washing by increasing loads up to 4.5-5 kg is hardly possible. In addition, it is practically impossible to put 5 kg laundry in the drum of a washing machine. Full loads are only possible when the machine is completely filled with large voluminous and heave cotton pieces such as folded towels, sheets and jeans (Uitdenbogerd *et al*., 1998). In practice the reduction potential of loading higher will be much lower than calculated in this study.

- Hot fill: trends in washing temperatures are in the direction of washing more and more at 40°C, which makes the reduction potential of hot fill washing machines less. Besides, the infrastructure for warm tap water in Dutch households is often not adapted to connect washing machines. Already in the eighties this reduction option was discussed, not much is expected of this reduction option in the future.

Comments related to drying

- It is assumed that the energy requirement for ventilation and heat loss (e) for drying laundry depends on the load weight (f_w) and rest humidity (f_{rH}) of the laundry. A '+' can be used when it concerns heat loss for a condensation tumble drier, and '–' when ventilation for gas fired and air vented tumble driers is taken into account. In formula: $(E \pm e) * f_w * f_{rH}$. E stands for the electricity use by the tumble drier.
  This however gives a different result compared to $(E * f_w * f_{rH}) \pm e$. Although no figures are available, it is likely that as the energy requirement for the dry cycle itself depends on the load weight and rest humidity, this accounts for heat loss and ventilation air as well.

- It is assumed that most of the heat of the air-vented tumble drier is exhausted outside the house and does not contribute to the heating of the house (as with condensation driers).

Comments related to textile materials

- For the different materials related to insulation wool is taken as an example as a study was found where actually was tested how one insulation unit of wool can compensate for a temperature's degree difference. Besides this wool needs specific laundering treatments which are energy friendly. However, from a greenhouse point of view, wool is 4 times unfriendly than other materials because of the methane emitted by sheep (Potting & Blok, 1995). Probably synthetic materials such as fleece are from this point of view a better alternative, however, the use and maintenance practices are likely to be different from wool.

Recommendations

For the integration of washing, drying and textile materials and related energy requirement should be investigated:

- influence of material, article type and article size on energy use for both washing and drying (laboratory research),
- volume of ventilation air in relation to weight load and to rest humidity of wet materials (laboratory research),
- weight load, material, article type and article size in relation to the frequency of drying in summer versus winter for air vented / condenser drier owners (research in households about household practices).

The one who finds a system for flexible drums + tubs (other than load automat and fuzzy control) will make a major breakthrough in adapting the energy requirement to load.

Although more space for line drying costs energy, it might be worthwhile to think about how such a space could conveniently be incorporated in small houses, using for example natural draught, as the energy needed to build extra space weighs out the energy needed for tumble drying.

Other measures that could be taken are:

- advice to users how to use tumble driers efficiently and optimally,
- tips (e.g. on television) related to the interaction of textiles, washing and drying how to save energy,
- program to increase supply and purchase of washing machines with high spin-drying capacity,
- research for spin-drying tumble driers (large drum),
- promotion of green electricity,
- promotion of indoor comfortable warm clothing that does not need to be washed often.

8 CONCLUSIONS

The total average energy requirement is calculated for the users' situation, first for MJ/kg, then for MJ per household per year. The users' situation includes an average washing temperature of 50°C, an average load weight of 3.5 kg (washing) and 3.3 kg (drying), a rest humidity of 60% after spin-drying, appliances in stock (as opposed to market best appliances) and energy related to ventilation (air-vented driers) and heat loss (condensation driers). The standard test situation only includes: washing at 60°C, 4.5-5 kg loads and a rest humidity of 70%. For washing figures are averaged for tumble drier owners and non-owners. For drying the figures are used for tumble drier owners. As air vented driers use a lot of air (225 m3) new air needs to be heated to room temperature. Condensation driers leak heated process air to the room, which saves a bit of energy. Eventually the direct energy requirement for both types of driers is more or less the same (5.5 / 5.6 MJ/kg). The primary energy for washing is 4 MJ/kg laundry, for drying 6.3 MJ/kg. The in total 10.4 MJ/kg consist of 8 MJ direct and 2.3 MJ indirect energy.

For the household situation this is on average 4.1 GJ/year (taking into account the penetration rate of 50% of tumble driers). The maximal energy requirement is 5.9 GJ/hh.y. In total 560 kg laundry is washed and 267 kg is dried per household per year. Although the average load weight is 3.5 kg, load weights are lower for smaller families. With family size the frequency of washing thus increases relatively slowly. The washing frequency is between 62 for one person households and around 400 for households of 4-5 persons, and on average 159 times/year. Tumble drier owners tumble dry on average 90% of their laundry, although it is not checked that probably tumble drier owners have more laundry, which would lower this percentage. The penetration rate of tumble drier owners is 50%, so in total averaged percentage of laundry that is tumble dried by a Dutch household averaged is 47%.

When line drying in the house the relative humidity of the room where the laundry is line dried will rise significantly, whereas the air temperature hardly changes.

Loading tumble driers higher than 3.3 kg saves 0.5 MJ/kg, but lower loads save in absolute terms more energy. For one article (100-500 grams) to a weight of approximately 2.5 kg the drying costs relatively too much energy to be interesting. Loads higher than 2.5 kg save significantly in absolute figures, whereas relatively the loss is not so important.

When energy for ventilation is taken into account, line drying does not save as much as generally expected.

The relevant alternatives that are discussed in this study are summed in the following table (Table 7). For comparison the energy requirement of the present users' situation is included (although not taking into account the penetration rate of tumble driers).

Table 7 Energy saving potential of reduction options discussed in this study, in [MJ/kg or GJ/hh.y]

Washing (4 MJ/kg)	± [MJ/kg]	Drying (6.3 MJ/kg)	± [MJ/kg]
~ load higher	- 0.5	~ load higher	- 0.5
~ small 3 kg machine	- 0.4	~ lower rest humidity	- 1.0
~ market best	- 0.5	~ market best	- 1.1
~ lower wash temperature	- 0.5	~ gas-fired	- 1.2
~ hot fill	- 0.5	~ line drying	- 4.6
		~ seasonal use (air vented driers; savings for ventilation air only)	- 0.7
		~ space for lines (1.2 m^2)	+ 0.2
Textiles		**Other**	± [MJ/kg]
	[GJ/hh.y]	~ contracting out	+ 3-5
~ wool	- 1.9	~ life time extension	
- heating house	- 4.8	- more hours per appliance	- 0.2 / 0.3
- extra clothing	+ 2.6	- e.r. for better materials	+ 0.01
- extra washing	+ 0.3	~ users intensity	-
~ co/po	[MJ/kg]		
- washing	- 0.2		
- drying	- 1.6		

Careful use of the tumble drier offers promising reduction potentials, and careful use can consist of several practices that can be changed. The results for washing and textiles are also relatively promising. The results for other reduction options such as contracting out and life-time extension are meagre.

- If households wash and dry in the most efficient way, they can save about 40% of the average energy requirement for washing and drying. The total energy requirement per washed and dried kilogram cotton textile lowers from 10.3 to 6.1 MJ. This will include the options 1. market best washing machines, 2. washing with 4.5 kg loads, 3. washing at 40°C, 4. spin-drying to 50% rest humidity, and 5. drying with gas fired driers.
- The most determining factors for energy reduction in general are (compared to a standard load) 1. washing at 40°C (factor 0.54), 2. drying with not a full load (factor .72), 3. using a gas fired drier (.47) and 4. spin-drying up to 50% humidity (factor .74). Three of the four are related to drying!
- The reduction option line drying still takes energy (6.3 - 4.6 = 1.7 MJ/kg). The energy requirement for drying and ventilation will be 1.7 MJ/kg cotton textile, a reduction of 73% for drying. Adding this to market best washing machines and washing at 40°C the energy requirement is 3 + 1.7 = 4.7 MJ/kg, a reduction of 54% compared to the present situation.
- Contracting out the laundry results in a higher energy requirement per kilogram washed textile. Extending the lifetime of the washing *and* drying equipment by better materials results in a reduction of 0.4 to 0.6 MJ/kg, 4 to 6% of the total average energy requirement for washing and drying.

The acceptance of reduction options is not discussed in this study. It can be expected to the option less heating by wearing warm textiles is relatively unacceptable because the trends in heating during the past decades have been the opposite. However, especially in relation with drying, a change of materials might have potential, both for the theoretical reduction potential as for the acceptance by households.

Figure 3 gives an overview of the energy requirement for washing and drying and the options to reduce the total primary energy requirement. It shows the total average primary energy requirement for washing and drying one kg cotton textile.

- The first bar shows the energy requirement of a household with a tumble drier. The users' situation is taken into account, i.e. wash cotton at 50°C, 3.5 kg wash load, efficiency of the washing machine in stock, spin-drying up to 60%, dry load of 3.3 kg, with the efficiency of a tumble drier in stock and energy related for ventilation/heat loss.
- The second bar shows for washing the same as for the first bar, for drying: line drying and the energy needed for ventilation.
- The third bar shows the reduction options market best washing machine, washing machine fully loaded and washing at 40°C, spin-drying up to 50%, fully loaded tumble drier and gas-fired tumble drier.
- The last bar shows the reduction options market best washing machine, full loads and washing at 40°C, line drying including energy needed for ventilation.

Also in this figure can be seen that even with careful use of tumble driers the energy requirement can be lowered significantly.

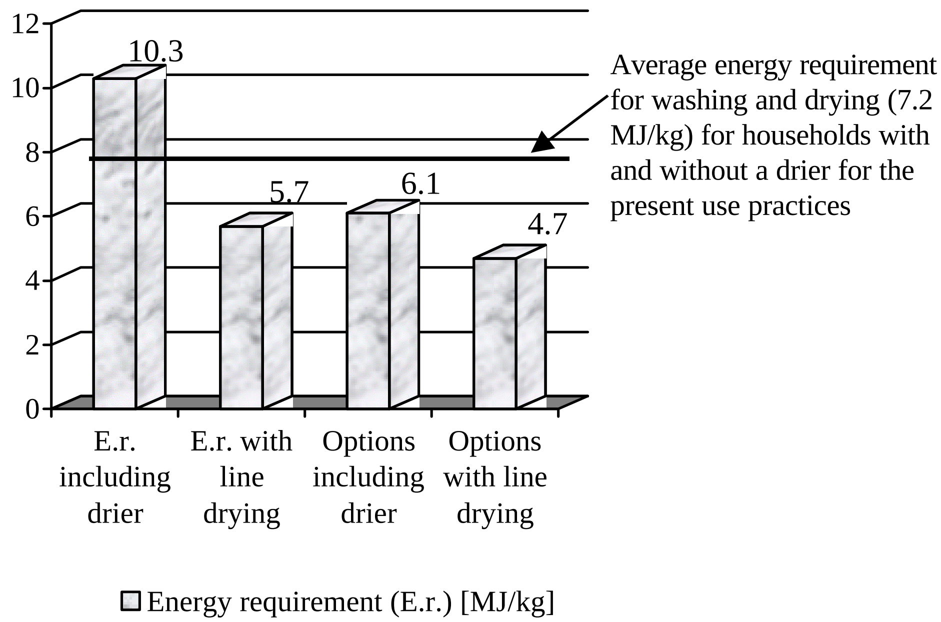

Figure 3 Total average primary energy requirement (e.r.) for washing and drying one kilogram cotton textile [MJ/kg] when dried with a drier and by line drying; with and without reduction options

The options ‘contracting out’, ‘sharing equipment’ and ‘extending lifetime’ are not taken into account in Figure 3.

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