Efficiency in the production and preparation of biomass for energetic utilisation

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Abstract:
The growing demand for renewable resources means a greater emphasis must be placed on more efficient processes. More attention must be focused on how the key resources 'land,' 'water' and 'energy' are used. The focus of the analysis presented in this paper centres around efficiency with respect to the energy and land balance. Using as an example the production, preparation and conversion of traditional energy crops on the one hand and of wood from short rotation coppice (SRC) plantations on the other, the differences in the results in terms of the efficiency and effectiveness achieved in the cultivation of both crop types for electricity and heat production will be shown. In terms of efficiency especially, the savings in the energy input into SRC during the first step in the production chain is five times higher than the efficiency of traditional agricultural crops. The use of special technologies such as dome aeration technology to dry the biomass produced can also contribute to greater energy efficiency.

Keywords: biomass, energy efficiency, supply and conversion

1 Introduction

Land, water and fossil fuels are the major global resources. The manner of use of these limited resources reflects human rationales, responsibility and, as a consequence, sustainability. In addition to a dwindling supply of these resources due to their finite nature, the contrasting regional demographic developments also serve to limit their availability, and any increase the intensity of their use. Between the years 1961 to 1997 the available area of cultivated land per capita used for the production of food declined from 0.44 ha to 0.26 ha. This area will continue to decline to about 0.15 ha by the year 2050 (Anonymous, 1997). According to FLASBARTH (2011), around 100 ha of land are sealed in Germany daily as a consequence of the construction of new buildings and roads. An even greater decline is occurring in terms of the forest area per capita of the world's population. It has been forecast that, by the year 2050, only a quarter of the forest area that existed in 1960 will remain (SCHULTE, 2007; FAOSTAT, 2007; UN, 2005).

The greater emphasis on the use of renewable sources of energy in the national supply and demand structure has shifted biomass into a central position. It is expected that by the year 2050 almost a quarter of the national energy demand in Germany can be met by biomass (FNR, 2011) (figure 1). Roughly half of this biomass will be produced on an agricultural land area of around 4 million ha, with an assumed yield of 10t_{atro} ha^{-1} a^{-1}(t_{atro} … tons absolute dry mass). Dendromass derived from forestry and allocated to energy use will account for about 20 %.

An estimated 740 PJ could be generated by energy plants by the year 2050. The increased use of biomass for energy production and the resultant competition for the use of land with food production has become a central topic of discussion (SPIEGEL ONLINE, 2011). Based on current German food consumption habits, with respect to food of both plant and animal origins, a complete securing of nutritional needs through national production would mean that less than 2 million ha of agricultural land remain for the cultivation of renewable energy resources (RAUH & HEIßENHUBER, 2008). Through food imports additional land in Germany can be freed up for the cultivation of energy plants, however. In recognition of this situation, a preferential selection of those production and supply lines achieving comparatively high rates of efficiency in the energy balance is necessary. Only a high level of efficiency can ensure that a large proportion of the energy won is not used up in the production, preparation and conversion phases, thereby rendering the energy generation largely 'illusory.'

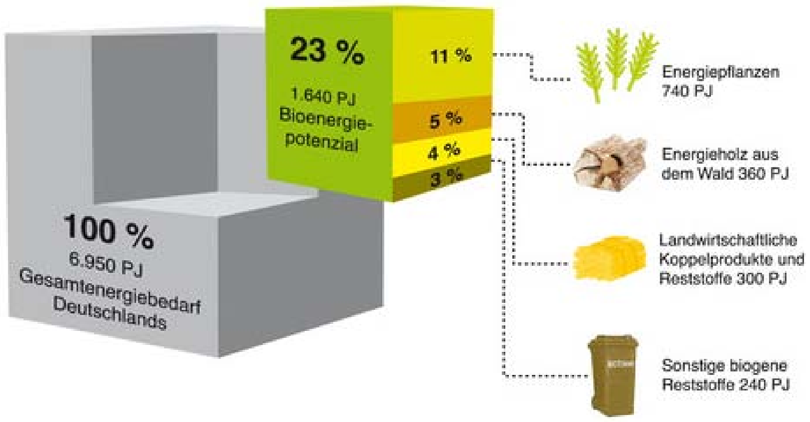

Figure 1: Estimated bio-energy potential in Germany in the year 2050 (FNR 2011)

In contrast to plants used in food production, with energy plants it is possible to choose from a variety of options. Important in this regard is the form in which the biomass accrues at the time of harvest, from the perspective of the technological suitability for energy generation. Of equal importance are the net energy yield per unit area and the degree of energy efficiency achieved over the entire chain, from production to preparation.

A comparison of the major energy plants, and the corresponding production and preparation procedures, in terms of their energy efficiency presents an interesting scientific exercise and is worthwhile in order to recommend preferred options.

2 Methods

The terms efficiency and effectiveness are often viewed in conjunction, without any clear separation of their meanings. *Efficiency* and *effectiveness* originally stem from the operations research branch of science. The definition of these terms in the scientific literature and the goals attributed to each are not the same (TILEBEIN, 2004), however. In the definition provided by AHN & DYCKHOFF (1997) both terms are allocated to a common system of goals. They defined effectiveness as "do[ing] the right things" and efficiency as "do[ing] the right things right." These definitions link both terms rationally and lie at the heart of the following considerations.

Efficiency in the context of energy comprises the ratio of result to effort as a quotient of OUTPUT and INPUT. INPUT consists of all of the fossil energy used in direct and indirect form according to the cumulative energy expenditure (*kumulierter Energieaufwand*, KEA) (VDI, 1997). The balance is made at the level of 'primary energy'; the primary energy content of all forms of directly applied energy, energy expenditure for auxiliary materials and the energy used in the manufacture, operation and disposal of machinery and facilities are calculated. Solar energy, water and natural nutrients represent free energy and are not taken into consideration. In the production of biomass, in particular, the proportion of free energy is especially high and efficiency values well in excess of '1' ensue. In the following process segments, by contrast, with very few exceptions no 'free energy' comes into effect, rather the process predominantly involves the direct or indirect input of energy, primarily from fossil sources. As a consequence, the original proportion of 'free energy' is gradually reduced und the energy efficiency value sinks. The challenge for science, therefore, lies in designing approaches for the capture, preparation and provision of biomass as an energy source in such a way that the high energy efficiency attained in the early part of the process is maintained through to the end. This means minimising the use of fossil energy sources in all subsequent preparation and conversion steps.

3 Efficiency in the production and supply of biomass

Biomass can be prepared in the form of phytomass or dendromass. Wood – produced by means of fast growing trees on agricultural land – is one of these variants and should be included in the spectrum of options along with the various agricultural crops (cf. RÖSCH et al., 2010). This gives rise to multi-faceted, variable solutions from which optimal solutions should be chosen by means of decision supports. The objective should be a high 'net energy yield' per unit area. At the same time, the necessary energy requirement over the whole process chain should be minimal, so as to achieve a high level of energy efficiency. Selected particulars with respect to the efficiency and effectiveness of the production and preparation of various forms of bioenergy cited in the relevant literature are presented in table 1.

Table 1: Energy efficiency (output : input) and energy effectiveness (output less input per hectare and year) for selected renewable raw materials

Product	Balance limits	*Efficiency* output : input	*Effectiveness* output – input per hectare and year GJ ha^{-1}a^{-1}	Comments	Authors
Poplar wood	SRC – establishment to harvest, drying, site restoration, incl. WC transport (short range) to delivery point	**60 : 1**	**177**	Degree of efficiency of thermal conversion included, no mineral fertilisation	SCHOLZ & KAULFUß (1995)
	SRC – establishment to harvest, drying, site restoration	**64 : 1**	**177**	Wood chips transported to field margin, no mineral fertilisation, application of dome aeration process for drying	KANZLER (2010) (supplemented)
Willow wood	SRC – establishment to harvest, and (short range) transportation	**22 : 1**	**172**	Includes mineral fertilisation (= 50 % of the total energy input) and WC transport (50 km)	BÖRJESSON (1996)
Turnip rape (cf. rape)	Soil preparation to transfer at point of delivery	**3 : 1**	**24**	Includes preparation / drying and 70 km lorry transport to RME plant	MIKKOLA et al. (2011)

Rape	Soil preparation to harvest	**2 : 1**	**23**	For a rape seed yield of 2 t ha^{-1} with 24 GJ t^{-1} energy content	VENTURI & VENTURI (2003)
	Soil preparation to harvest	**5 : 1**	**54**	For a rape seed yield of 70 GJ ha^{-1} or 3 t ha^{-1}	BÖRJESSON (1996)
Sugar beet	Soil preparation to harvest, and transport to field margin	**3 : 1**	**62**	Highest output/input values at minimal input, range 2.8-3.2	VENTURI & VENTURI (2003)
	Soil preparation to harvest, and transport to point of delivery	**7 : 1**	**163**	50 km lorry transport to plant included	BÖRJESSON (1996)
	Soil preparation to harvest	**15 : 1**	**262**	Minimal input intensity and optimal management	REINEKE et al. (2010)
Barley	Soil preparation to harvest, drying, and transport to point of delivery	**3 : 1**	**27**	100 km lorry transport to bioethanol plant included	MIKKOLA et al. (2011)
Silage maize	Soil preparation to harvest, and transport to field margin	**3 : 1**	**62**	Calculated yield: 86 GJ ha^{-1}	VENTURI & VENTURI (2003)
	Soil preparation to harvest, and preparation for biogas plant	**15 : 1**	**407**	Calculated yield: 236 decitonnes ha^{-1} or 435 GJ ha^{-1}	EDER et al. (2009)
Pine wood from forests	Afforestation to preparation, with transfer to forest road	**54 : 1**	**74**	Forestry, industrial pine wood, mean annual increment: 9 m^3 ha^{-1} a^{-1} (BWI, 2004)	SCHWEINLE (2000)

SRC – short rotation coppice; WC – wood chips; RME – rape methyl esther

The method employed by the various authors was based on the standardised balancing approach of the ‘cumulative energy expenditure’ (KEA). However, the balance limits used by the different authors do not always correspond entirely. The numbers presented represent an opportunity to make a general comparison only, but this is sufficient in the context of the objectives stated at the outset of this paper.

If the biomass produced is ultimately to serve the generation of heat and electricity, the energy yield inherent in the final product is relevant. In terms of energy efficiency, the results of the comparison between the various production processes for the energy crops considered are sobering. The ‘traditional energy crops’ such as rape, maize and cereal in particular achieve in the sum of production and preparation a maximum value of 15 in terms of the output to input ratio. In certain cases, however, the yields assumed by the various authors, and the resultant efficiency values, differed considerably. In the case of maize used for silage, the energy yield per unit area varied by a factor of 5. This had a corresponding effect on the calculated efficiency values. By contrast, the efficiency values obtained for wood of between 50 (forestry) and 60 (SRC) appear realistic. The application of mineral fertilisation in SRC accounted for up to 50 % of the total energy expenditure in the energy balance, serving to ‘halve’ the energy efficiency (see table 1). In terms of effectiveness (‘net energy yield’), SRC performed better than the alternative agricultural processes for energy crop production – with the exception of maize and sugar beet. The reason for these positive findings in relation to the production of biomass by means of WOOD grown in SRC is primarily as a result of the savings that arise from the lack of a need for any soil preparation, sowing, fertilisation or tending measures for the entire life cycle of the crop of in excess of 20 years after the initial crop establishment.

4 Preparation and provision of biomass

The material characteristics of the various energy plants at the time of harvesting require further preparation so that the subsequent steps – transport, handling, storage and particularly the eventual conversion to usable energy – can be managed rationally. This preparation includes:

- the removal of water (drying) and
- increasing the density of the material (pressing, pelleting and briquetting).

A significant added value can be achieved as a result of the homogenisation of the material in conjunction with a subsequent pelleting to prepare a standardised fuel of consistent quality. In each of these processes, various levels of energy are used, however. This, in turn, has a negative impact on the energy balance with respect to energy efficiency. The need for these additional steps should, therefore, be carefully assessed and their effect on the energy balance quantified.

Drying

The various biomass types must be further processed for an energetic use. In the simplest case, this may involve merely drying the material. As a general rule:

“With all chemical-thermal processes, a proportion of the energy contained in the fuel directly proportionate to the water content must be expended and subtracted from the usable energy in order to warm and vaporise the water (BRUMMACK, 2010).”

The usable energy content of wood can be calculated according to the following relationship:

$$H_i = (1- w)\, H_{i,atro} – [w\,(c_{p\,H2O,\,fl}\,(\vartheta_S - \vartheta_{Br}) + \Delta H_v)] \qquad (1) \qquad \text{where}$$

H_i - calorific value at w [MJ kg^{-1}] ϑ_S - boiling point of water [K]

w - water content [kg kg^{-1}] ϑ_{Br} - fuel temperature [K] applied for $\vartheta_{Br} \geq 0°C$

$H_{i,atro}$ - calorific value when absolutely dry [MJ kg^{-1}] $c_{p\,H2O,\,fl}$ - specific heat of liquid water

ΔH_v - latent heat of water $c_{p\,H2O,\,fl} = 4.187\ 10^{-3}$ Mj $kg^{-1}K^{-1}$

[MJ kg^{-1}], at 100°C: $\Delta H_v = 2.257$ MJ kg^{-1}

The term in equation 1 can be omitted for approximate calculations (BRUMMACK, 2010). In figure 2

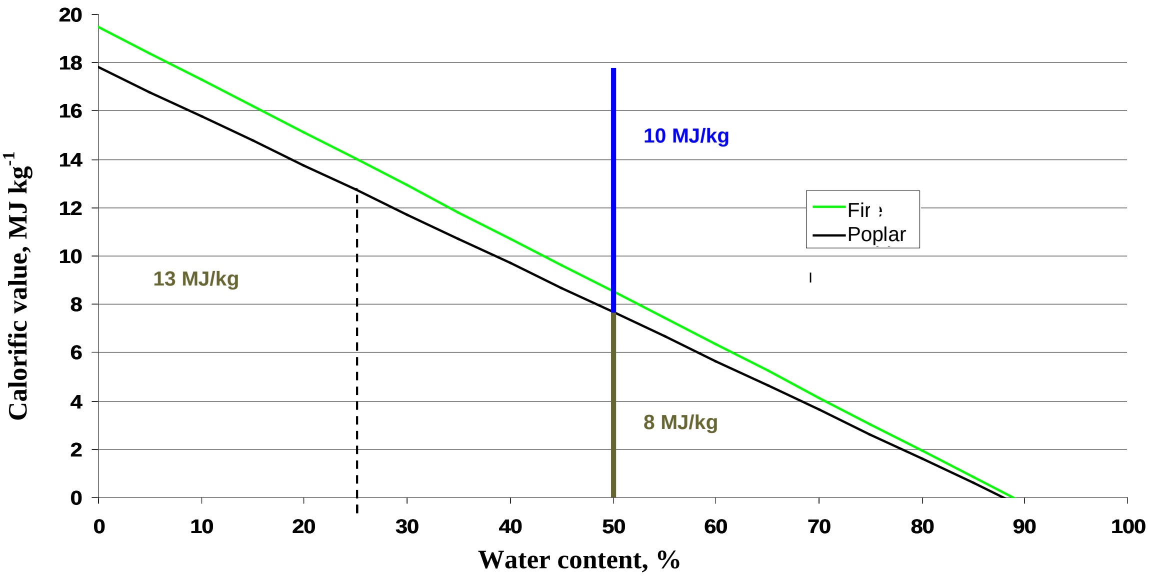

Figure 2: Correlation between the water content and the calorific value of fir and poplar wood the calorific value of fir and poplar wood is plotted relative to the water content. Whereas the calorific value of wet poplar wood is roughly 8 MJ kg^{-1}, the value increases to around 13 MJ kg^{-1} upon a reduction of the water content to 25 %. This factor should be taken into consideration when targeting high efficiency.

A variety of processes can be used to dry wood chips produced in SRC. These may contribute to either maintaining or reducing efficiency. In addition to 'technical drying' processes using either cold or warm air, another drying option is the self-heating of wet biomass induced by microbial activity in the 'dome aeration process' (*Dombelüftungsverfahren*) (figure 3).

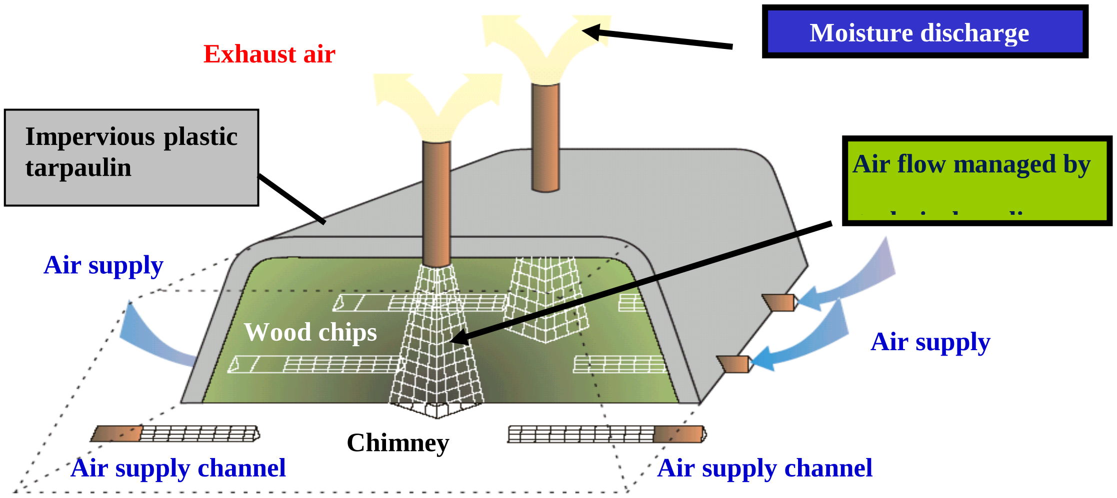

Figure 3: The dome aeration process (Dombelüftungsverfahren)
Source: BRUMMACK (2005); TROIS & POLSTER (2007), modified

The parenchyma cells that initiate this warming process decompose fine organic components but without attacking the dendromass. As was mentioned, the drying of biomass prior to energetic use improves the energy efficiency considerably, if efficient drying processes are applied. In the example presented (cf. table 2), the energy content of the wood chips (lower calorific value) increases by a factor of 1.6 in the dome aeration process, whereas drying using warm air results in an efficiency value after drying that is only a little over half the pre-drying value. Drying with cold air, and the corresponding expenditure of 'technical energy,' pays dividends, with an increase in efficiency by a factor of 1.2.

Compacting

Preparation processes have a further influence on the energy efficiency, with culm-like biomass types requiring compacting (pressing, pelleting or briquetting) for a subsequent energetic use. Whereas the compacting of culm-like material such as straw or miscanthus is a general precondition for energetic use, wood is traditionally used without any such preparation. Wood can, however, be pressed to briquettes or pellets, and so attain an added value. Unlike wood chips, wood pellets have constant material characteristics, are a conveyable bulk good and are characterised by a very low water content (<10 %). Wood pellets are a standardised fuel (e.g., DIN 51731, Ö-NORM M 7135). Due to their characteristics wood pellets can be readily transported, transferred and stored, and the fully automated running of both small and medium-sized heating systems is possible with pellets. However, this improvement of the energetic and logistical material characteristics requires a corresponding energy expenditure in the preparation chain. OBERNBERGER & TIECK (2009) cited an energy expenditure of 410 MJ_{elt} and 4 323 MJ_{th} for every tonne of pellets with a starting water content of the wood of 55 % (table 3). This gives an estimated value for the primary energy expenditure for pellet production of around 5.5 GJ t^{-1}.

Table 2: Energy efficiency of various wood chip drying processes (material: wet wood chips derived from poplar SRC) (GROßE, 2006; KANZLER, 2010)

	Wood chip drying process	Output : input pre-drying w = 50 %	Input MJ/t_{atro}	Output: input post-drying w = 25 %	Comments
1	*Cold air drying*	(7 670 MJ/t_{atro} : 208 MJ/t_{atro}) **37 : 1**	77 [1)]	13 260 MJ/t_{atro} : 285 MJ/t_{atro}) **46 : 1**	Input: electric fan, including flow channels; HARTMANN & STREHLER (1995), supplemented
2	*Heated air drying*	(7 670 MJ/t_{atro} : 208 MJ/t_{atro}) **37 : 1**	416 [1)]	13 260 MJ/t_{atro} : 624 MJ/t_{atro}) **21 : 1**	Input: heating unit and electric aeration fan, including flow channels; HARTMANN & STREHLER (1995), supplemented
3	*Dome aeration process*	(7 670 MJ/t_{atro} : 208 MJ/t_{atro}) **37 : 1**	12	13 260 MJ/t_{atro} : 512 MJ/t_{atro}) **60 : 1**	Input: 3 domes / 8 canals, 540 m^2 protective sheet, initial values according to BRUMMACK (2006), supplemented[1]

w = water content SRC = short rotation coppice

[1)] added to the direct energy expenditure (electricity and heating) cited by HARTMANN & STREHLER (1995) are expenditures for the materials (energy expended in products) used in fixtures and for protective sheets of identical size to those used in the dome aeration process

The energy expenditure required for the construction and maintenance of pelleting equipment was not quantified by the authors. Based on WALLE et al. (2007), this accounts for 5 % of the direct energy expenditure required for pellet production, corresponding to 0.3 GJ t^{-1}. This results in an estimated energy expenditure for pellet production of 5.8 GJ t^{-1}. Approximately one third of the calorific value of wood is, therefore, consumed solely in the production of the pellets.

Table 3: Energy expenditure in the pelleting process (based on fresh wood with a water content of 55 %) (OBERNBERGER & TIECK 2009)

	Energy expenditure, MJ t^{-1}	
Procedure	**Electricity**	**Heat**
Drying	85.7	4 320.0
Reduction	67.3	0
Pelleting	183.6	2.9
Cooling	7.2	0
Machinery	66.2	0
Sum	**410.0**	**4 322.9**

5 Conclusions

If one considers the land area required for the generation of energy using biomass, it becomes evident that decision making with regard to the selection of a suitable 'energy plant,' and also either for or against a particular production process, requires the incorporation of energy efficiency considerations. If it is assumed that in Germany in the year 2050 around 740 PJ are to be provided by the production of 'energy crops,' as described in section 1, any such consideration should include a comparison of the alternatives *maize* and *poplar wood* from SRC. The results of just such a comparison are presented in table 4, and should be deemed a decision support.

Table 4: Energy balance per hectare in a comparison of central electricity and heat generation with maize (whole plant) and poplar wood chips (basic data derived from table 1)

		Maize chaff, whole plant	**Poplar (SRC)**
Biomass yield	t_{atro} ha^{-1} a^{-1}	24	10
Gross energy yield	GJ ha^{-1} a^{-1}	435	180
Energy input	GJ ha^{-1} a^{-1}	28	3
Net energy yield	GJ ha^{-1} a^{-1}	407	177 [1)]
Energy yield (electricity and heat) [3)]	GJ ha^{-1} a^{-1}	348[3)]	150 [2)]
Requirement for 740 PJ a^{-1} / Basis: electricity and heat	10^6 ha	2,13	4.93
Input- Requirement for 740 PJ a^{-1}	PJ a^{-1}	148	57

[1)] wood chips (w = 25 %); [2)] biomass combined heat and power (CHP) plant, degree of efficiency = 0.85; [3)] biomethane production with centralised conversion to electricity in a CHP plant (efficiency values according to DRESSLER et al., 2011)

If the biomass produced for every hectare is converted to electricity and heat in a central biomass cogeneration plant, taking into consideration all of the INPUT expenditures, the target of 740 PJ in 2050 mentioned at the outset can be achieved by means of short rotation coppice plantations on approximately 2.5 more of the land area, with a considerably lower energy input (30%), than in the case of biomethane produced from whole maize plants with subsequent electricity and heat generation. One may, therefore, conclude the following:

Effectiveness is "do[ing] the right thing," which means obtaining energy from biomass. Efficiency is "do[ing] the right thing right," which means producing this biomass primarily by means of fast growing trees managed in short rotation coppice plantations.

6 Summary

Biomass is growing in importance as a resource for energy generation, whether derived from agricultural crops or from fast growing tree species. The different plant types and the processes applied can be compared under the aspects energy efficiency and effectiveness. The results, in the form of energy balances from production to the generation of electricity and heat, indicate the benefits of the use of fast growing tree species and of wood for additional energy generation. In comparison to maize, an agricultural crop with the highest biomass yields, heat and electricity can be obtained from short rotation coppice plantations with species such as poplar comparatively effectively and efficiently. With just one third of the energy input required in the production process of poplar wood chips in comparison to silage maize, it is possible to generate the same amounts of heat and electricity using 2.5 more area of land required to produce biomethane from silage maize with subsequent heat and electricity generation.

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