Efficiency evaluation of energy crop digestion plants

Braun, R.1); Madlener, R.2) and Laaber, M.1)

1) BOKU - University of Natural Resources and Applied Life Sciences, Vienna, Department for Agrobiotechnology, IFA-Tulln, Institute for Environmental Biotechnology; Konrad Lorenz Str. 20, A- 3430 Tulln, Austria, Email: rudolf.braun@boku.ac.at

2) Centre for Energy Policy and Economics (CEPE), Department of Technology, Management, and Economics, Swiss Federal Institute of Technology Zurich (ETH Zurich), Zurichbergstrasse 18 (ZUE E), CH-8032 Zurich, Switzerland, Email: rmadlener@ethz.ch

Abstract

This paper reports on an ongoing investigation aiming at the definition and measurement of energetic, business economic, ecological, and socio-economic parameters characterising the overall production chain of biogas systems and their performance. The production chains studied range from the cultivation and supply of energy crops (including on-site transport and storage), to bioconversion (pre-treatment, digestion), on to final biogas utilisation and use of the digestate. In total about 250 parameters were identified, allowing for an accurate, multi-dimensional description and evaluation of biogas recovery from energy crops. Parameters included allow for a detailed functional description, and comprise measurable performance parameters as well as derived (calculated) efficiency parameters. Based on the pre-defined list of parameters, detailed data have been collected over the last two years from a set of 40 full-scale and operational Austrian biogas plants. The collected data have been used to examine the productivity of the plants by means of data envelopment analysis (DEA). The performance of each plant, measured by multiple inputs and outputs, is compared with the most productive plants in the sample (best practice benchmarking). First results from the benchmarking analysis show considerable differences in production efficiency, depending on the choice of substrate, plant size, and operational conditions.

Keywords

Anaerobic digestion, biogas from energy crops, efficiency criteria, best practice bench-marking, data envelopment analysis, DEA

Introduction

Driven by the need to achieve ambitious political goals, such as the one under the Kyoto Protocol (-13% greenhouse gas emissions by 2008/12, relative to 1990 levels) or the Green Electricity Act 2002 (renewable electricity share of 78.1% by 2008), an effective promotion of renewable energy technologies has been pursued in Austria in recent years. In particular, feed-in tariffs between 10.3-16.5 Cents / kWh_{el} for ‘biogas’ electricity fed into the grid have led to a remarkable boom in the construction of agricultural biogas plants (Markard et al., 2005). As a consequence, the number of plants rose from 110 at the end of 2003 to more than 200 by the end of year 2004 (as a comparison: in Germany over 3,000 biogas plants are currently in operation). Both in Austria and Germany, the majority of the plants use mainly energy crops (silage) for digestion. However, up to now the promotion of energy crop digestion was hardly linked to efficiency criteria. As a result many different technologies and specific applications occurred on the market, some of which were not very energy-efficient and reliable.

Due to the attractive feed-in tariffs granted in Austria that are guaranteed for a duration of 13 years (BGBl, 2002), anaerobic digestion of energy crops currently mainly aims at the generation of electricity. As a consequence, regrettably, the heat energy produced in co-generation units remains largely unused. Even worse, many plants use electricity for cooling purposes, in order to prevent adverse effects from self-heating of crop digesters. By this means, in many cases up to two thirds of the available technical energy potential remains unused.

Generally speaking, the production chain of biogas systems is fairly complex. Every process step is associated with a potential loss of energy. A reduction of these energy losses can contribute to a better economic and ecological performance of energy crop digestion, enhancing overall efficiency. Optimisation potentials can be found at nearly every stage of the production process – starting from the cultivation and the supply of energy crops, via bioconversion (digestion), on to final gas utilisation and use of the digestate.

In 2004, IFA-Tulln initiated a monitoring- and benchmarking project that includes a detailed investigation of over 40 Austrian energy crop digestion plants. The project also aims at creating and establishing an evaluation system for the objective and transparent assessment and benchmarking of the productivity of biogas plants by means of energetic, business economic, ecological and socio-economic criteria, characterising the overall production chain of biogas. Since anaerobic digestion has the potential of reducing greenhouse gas emissions (Braschkat et al., 2003), an important objective of the project is to evaluate the environmental impacts through the overall “crops to energy” process. Finally, positive and negative socio-economic impacts have been accounted for to a limited extent by means of a questionnaire survey undertaken among plant operators (subjective valuation, supplemented by measurable data).

Material and Methods

Selection of biogas plants and data acquisition

Data acquisition was performed on site by means of personal interviews of plant operators. Representative samples were taken from the substrate, digester, fermentation residues, and the biogas. Representative cooling, safe transport and appropriate storage was scrutinised as well. Samples were analysed according to German Standard Methods (Anon., 2000). The biogas plants investigated were carefully selected and cover the entire spectrum of existing plant types and operations in Austria. The installations considered are geographically distributed over all nine of the Austrian provinces, ranging from small-scale installations in alpine agricultural regions in Western Austria to the larger scale operations and farm areas in Eastern Austria. Large plants up to 1,672 kW_{el} of electrical capacity were investigated as well as very small installations down to 18 kW_{el}. It was also tried to achieve a representative spectrum of the substrates applied. Both single substrate (energy crops) installations, as well as co-digestion plants (agricultural by-products, industrial bio-wastes) have been analysed.

Identification and definition of specific evaluation parameters

In order to describe a biogas plant comprehensively, it is necessary to collect specific data on the process technology as well as on the overall mass flow, and on business economic, environmental and socio-economic aspects. Parameters identified cover the areas (1) substrate provision, storage, pretreatment; (2) biogas production (digestion); (3) gas utilisation; and (4) digestate handling and disposal. For the individual thematic areas interfaces were defined, which allow for a clear allocation of the parameters to the thematic areas.

Parameter selection was discussed in a specialist group, mainly based on German experience gained in the monitoring of biogas plants (Weiland, 2004). More than 250 specific variables could be derived, describing the overall biogas recovery process in full detail. The parameters identified can be divided into 3 groups: (1) general functional description, (2) measurable process conditions, (3) calculable variables (Table 1). The headlines listed in Table 1 under the topics ‘substrate’, ‘digester’, ‘digestate’, and ‘biogas’, in each case include numerous sub-headings. Altogether more than 250 parameters were applied for a comprehensive description of the plants investigated.

Efficiency measurement of biogas plants by means of Data Envelopment Analysis

For the overall performance assessment of the biogas plants, Data Envelopment Analysis (DEA) was used (Farrell, 1957; Charnes et al., 1978, 1994; Seiford and Thrall, 1990; Cooper et al., 2000). DEA is a widely applied non-parametric linear programming method for comparative efficiency measurement. It allows the determination of an “efficiency frontier” of production processes. In contrast to alternative parametric econometric approaches, such as stochastic frontier analysis, DEA does not assume any specific functional form, thus avoiding problems of model misspecification. Moreover, it allows for the inclusion of non-economic (e.g. environmental impact, socio-economic) variables in the assessment, as well as the use of multiple inputs and outputs.

Apart from the identification of inefficiencies in production, DEA also enables to determine the scope for improvement of inefficient plants and/or to formulate precise goals for efficiency improvements. In this respect the method is also useful as a planning tool in technology management. It further allows for the consideration of both technical and economic efficiency (the former deals only with technological characteristics of production, while the latter also takes economic variables – such as cost and prices – into account). Finally, the analysis can be further extended to also take into account environmental and social impacts of technology use. Note that these may be positive or negative, and thus have

Table 1. Grouping of parameters applied for evaluation of the biogas plants investigated

General functional description	Measurable process conditions	Calculable variables
SUBSTRATE		
Quality / quantity Transport Storage Pretreatment Costs	COD[1] TKN[2], NH_4-N TS[3], VSS[4]	t / year Costs/year
DIGESTER		
Startup Investment costs Subsidies Annual costs Process steps Substrate dosage Digester type Digester equipment Digester mixing	T, Self heating pH, VFA[5], COD, TS, VSS TKN, NH_4-N Process energy demand Sludge recirculation	Residence time Hydraulic loading VSS degradation Biogas yield
DIGESTATE		
Storage type / cover Treatment / Dewatering Use	pH, COD, TS, VSS VFA, TKN, NH_4-N CH_4-formation Hygienic status	t / year
BIOGAS		
Gas holder Upgrading Quantity /utilisation	CH_4, H_2S	Calorific value Electrical efficiency
PERSONNEL EXPENDITURE		
SALES REVENUES / OVERALL ECONOMICS		
ECOLOGICAL- / SOCIO-ECONOMIC PERFORMANCE		

[1] Chemical Oxygen Demand; [2] Total Kjelldahl Nitrogen; [3] Total Solids; [4] Volatile Suspended Solids; [5] Volatile Fatty Acids

to be appropriately taken into account with respect to their impact on the ranking of a specific plant (or 'decision making unit'). The current analysis aimed at defining and establishing characteristic and to a large extent objectively measurable input and output parameters, that are able to comprehensively describe the biogas plants studied. By this means a comparative evaluation of the production efficiency of the biogas plants can be achieved. The detailed information on the overall production chain and on practical experience with biogas plants was fed into a database and used as an input for the DEA. For the exemplary analysis reported here, the parameters (1) personnel expenditure, (2) yearly amount of processed substrate and (3-5) annual yield of biogas, power and heat, respectively, were used.

Table 2. Performance figures of the technical monitoring and benchmarking

Parameter	Unit	Median[1]	min.	max.
Amount of processed substrate	$t_{Substrate}/d$	12.5	0.8	54.8
Hydraulic retention time	$m^3_{RV}/(t_{Substrate}/d)$	139	49	483
Organic load (dry substance)	$kg_{VSS}/(m^3_{RV}\cdot d)$	3.39	1.19	8.83
COD load	$kg_{COD}/(m^3_{RV}\cdot d)$	5.09	2.03	13.29
Amount of VSS	t_{VSS}/d	2.33	0.32	13.88
Biogas generation	Nm^3_{biogas}/d	1,461	232	8,876
Biogas productivity	$Nm^3_{biogas}/(m^3_{RV}\cdot d)$	0.89	0.24	2.30
Carbon degradation	%	81.34	67.15	97.09
Average biogas yield	Nm^3_{biogas}/kg_{VSS}	0.673	0.423	1.018
Methane content in biogas	%	53.01	49.01	67.01
Use of heat (process heat and end use)	% (rel. to total output)	28.9	0.0	87.6
Electrical efficiency	%	31.8	18.3	38.3
Degree of heat utilisation (end use)	% (rel. to total output)	14.7	0.0	43.3
Degree of utilisation of the energy contained in biogas (H_u)	%	46.9	27.5	80.2

RV: Reactor volume; H_u: Net calorific value; VSS: Organic dry substance

1) Instead of average values the median was calculated

Results and Discussion

Collection of performance data from biogas plants

The consolidated results from data acquisition and analysis are given in Table 2. Although just representing a minimum number of selected parameters, the broad range of results obtained can be clearly recognised. The amount of substrate processed varied beetween less than 1 t/d in the smallest installations up to 55 t/d in large plants. The biogas productivity ranged from 0.24 to 2.3 $m^3.m^{-3}.d^{-1}$. Correspondingly, the biogas yield varied between 0.42 and 1 $m^3.kg^{-1}$ VSS. A similarly broad range of corresponding results was found in the evaluation of the business economic parameters. The electrical efficiency was as low as 18% in the worst case, while over 38% was achieved in well operating installations. The degree of heat utilisation of about 15% (median) was generally low. Best performing plants could use more than 40% of heat, while many of the installations did not make any use of the waste heat from power generation. Forteen installations produce 100 kW, 11 produce 500 kW and 8 produce 250 kW elctrical power. Five were very small installations (50 kW_{el}) and three were bigger than 1 MW.

About 71 % of 59,000 t dry organic substance, used annually in the 41 plants considered, origine from energy crops, 12 % from manure and 17 % from other biogenic by-products and wastes. With a share of 53 %, maize dominates the crops used in digesters. Togehther with corn cob mixture (22 %) and maize corn (2 %) the overall share of maize amounts 77 %, followed by grass (9.4 %), grain (5.5 %) and several other crops (sun flower, wheat, clover). Concerning manure, pigs dominate (45.6 %), followed by cattle- (36.6 %), chicken- (7.9 %), horse- (6.3 %) and turkey manure (3.6 %). Food leftovers (20 %) dominate the co-substrates used, followed by flour mill by-products (14.4 %), oil processing- (11.3 %), sugar beet-(10.8 %), potato- (7.4 %) and various other wastes of minor quantity.

The majority of 99 plants considered runs 2-step digesters (85 %), 12 % use 3-step-, the remaining more than 3 digester steps. About 29 % of the plants run at 42^0C, 27 % at 40^0C and 22 % at 38^0C. Just 10 % operate at 48^0C and 12 % at 55^0C. The most common residence time is 100 days (32%), followed by 150 days (24 %), 200 days (15 %). Anyhow, 10 % of the installations use 250 days and 15 % even more than 250 days. Just 5 % use less than 50 days residence time. The resulting organic loading amounts 4 kg $VSS.m^{-3}.d^{-1}$ (32 %), 5 kg in 22 % and 3 kg in 20 % of the 41 plants considered. Seventeen plants use loadings between 6-8 kg, and 10 use loadings below 2 kg $VSS.m^{-3}.d^{-1}$.

Efficiency measurement of biogas plants

An important part of the research project was related to measuring the relative production efficiency of the biogas plants studied. ‘Relative’ in this context means that performance is measured relative to the plants with the best performance contained in the data sample. DEA allows to find the (imaginary) frontier curve of production efficiency, determined by the most efficient plants or ‘decision making units’ (DMUs) contained in the sample. Figure 1 shows the principle behind DEA for the example of two inputs, viz. time spent for plant operation and amount of substrate used (organic dry substance, ODS), respectively, and one output (amount of biogas produced), using a preliminary dataset for 37 Austrian biogas plants. As can be seen, plants C, D and E are the relevant DMUs for establishing the efficient frontiers. Relative technical efficiency of an arbitrarily chosen plant A is measured by the distance 0A’/0A, that of plant B is measured by distance 0B’/0B. The efficient plant C (efficiency score of unity) is the reference plant (or ‘peer’) for plant A, and plants C and D likewise for plant B. Note that in the graphic chosen inputs (time, ods_ann) are put in relation to output (biogas_ann), thus allowing for a two-dimensional representation.

In the following, some exemplary efficiency ranking output produced with the DEA software ‘DEA-Solver’ is shown (Cooper et al., 2000). Figure 2 depicts the result of a data envelopment analysis undertaken with a CCR-O[1] model specification for two inputs (ODS, time spent on plant operation) and two outputs (net electr. prod, total heat prod.) as an illustration. As can be seen, for a model that assumes constant returns to scale (CRS; i.e. when all inputs are increased by a given percentage output increases by the same percentage), plants 2, 6, 18, 21 and 30 determine the efficiency frontier (efficiency value of unity), while plants 42, 35, and 5 show the worst performance of all 43 plants considered.

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[1] Named after Charnes, Cooper and Rhodes (1978), output-oriented model specification (i.e. a model that aims at maximising output(s) for the observed amount of any input(s), in contrast to input-oriented models that aim at minimising inputs for producing at least the given output levels).

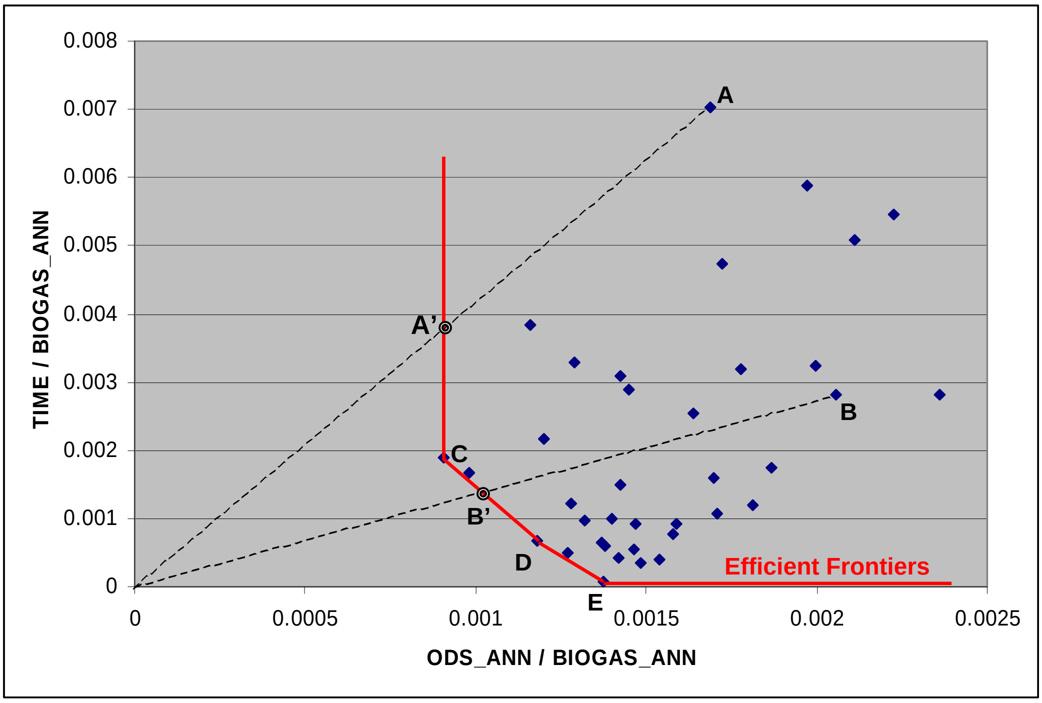

Figure 1. Illustration for an input-oriented DEA model specification with constant returns to scale (sample of 37 plants; inputs: amount of organic dry substance (ODS) used, time spent for plant operation (annual figures); output: amount of biogas produced (annual figure)

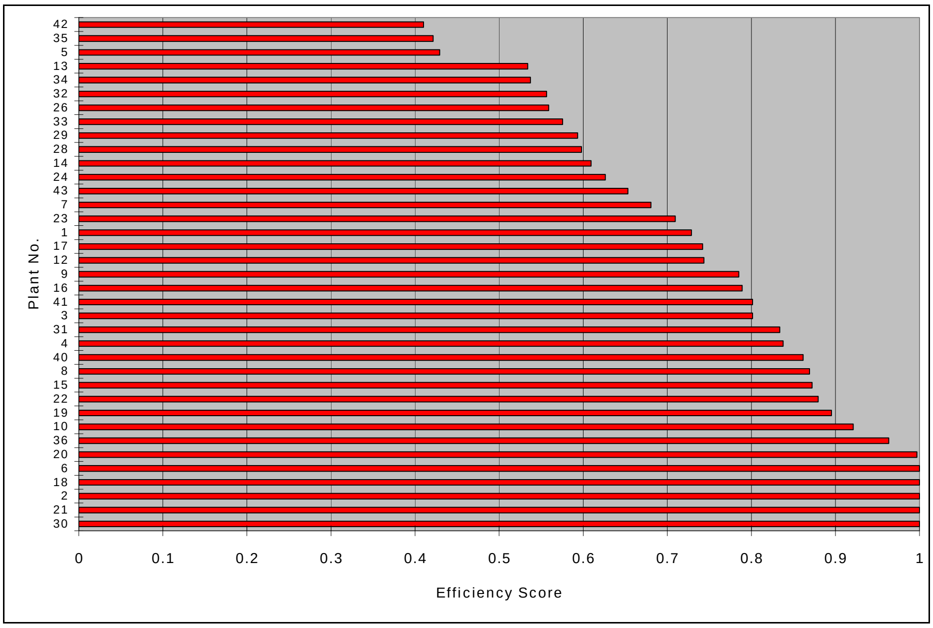

Figure 2. Data Envelopment Analysis with a CCR-O model specification (sample of 37 plants; inputs used: amount of organic dry substance, time effort; outputs used: net electricity production and total heat production)

Figure 3 shows another illustrative result, this time for an output-oriented variable returns to scale (VRS) model formulation (BCC-O[2]). With this DEA model, plants 2, 6, 12, 15, 17, 18, 20, 21 and 30 (i.e. a total of nine plants) form the efficiency frontier curve, while plants 35, 42 and 5 perform worst (i.e. plants 35 and 42 have changed their ranking).

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[2] Named after Banker, Charnes and Cooper (1984).

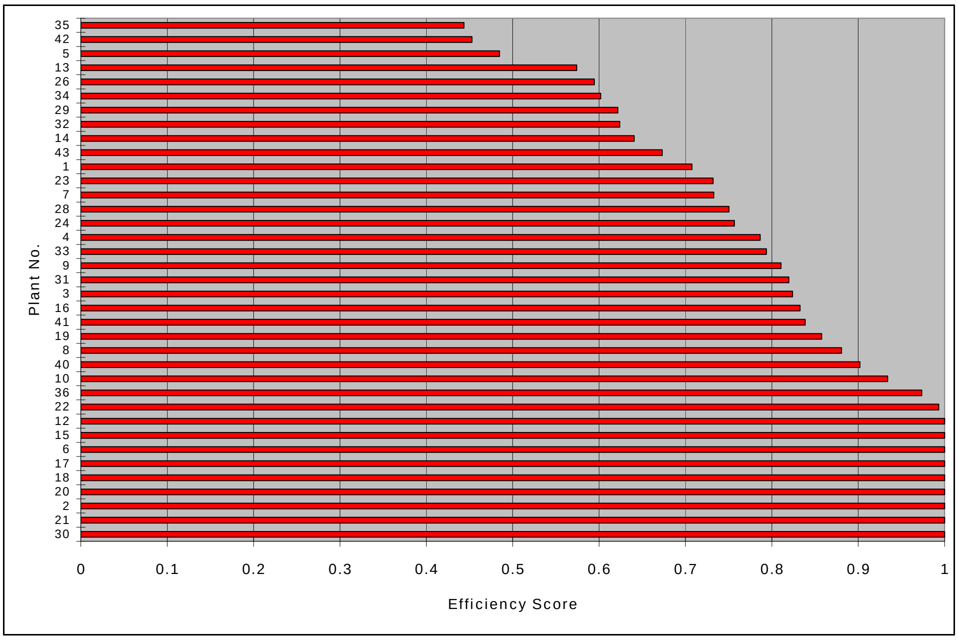

Figure 3. Data Envelopment Analysis with a BCC-O model specification (sample of 37 plants; inputs used: organic dry substance and time effort; outputs used: electricity fed into the grid, total heat production)

Further work is currently under way in which a whole battery of DEA model specifications is used against a comprehensive data set of 40 plants. The efficiency benchmarking also takes into account cost, value limitations, and the impact of certain environmental and social sustainability indicators on the efficiency score (ranking). In a further step, sensible minimum scores will be determined and used that can serve for a description of a quality label (or performance standard) for biogas plants. Obviously, in such an exercise it will be of crucial importance that the minimum scores employed are documented in a transparent way. Besides, since it is possible that depending on the DEA specification applied, plants may or may not be below the minimum standard, robustness of the rankings needs to be tested in a systematic way. Finally, it ought to be stressed once again that the best practice benchmarking undertaken with DEA is a relative one (i.e. plants performing just above the established threshold level for obtaining the quality label might fall below this threshold if, *cet. par.*, the performance of the most efficient plants is improved further).

Conclusions

An improved energetic, business economic, environmental, and socio-economic performance of biogas plants can lead to a higher degree of acceptance of the biogas technology as a meaningful and sustainable future alternative heat and power production system.

Based on the above-mentioned investigations, an extensive database was generated, which forms the foundations for the development of a transparent evaluation system for biogas plants that uses DEA as a pillar for best practice assessments. The evaluation system represents a management tool for comparing and balancing of assessment criteria, studying sensitivities to parameter variation, and defining efficiency criteria and targets for the future biogas market.

With the help of DEA, adapted to the specific needs of biogas system assessments (Madlener, 2005), productivity information is fed into a user-friendly best-practice evaluation system suitable for practical use. Based on this evaluation system, both existing and planned biogas plants can be assessed in a systematic way, and appropriate measures for further improvements of individual production stages as well as system optimisations derived. Based on the results, a quality label (performance standard) for biogas plants can be introduced that should provide useful for policy-makers, plant suppliers, consultants, end-users of biogas technology, and other stakeholders involved. Experiences from best practice biogas plants can avoid poor technological development and technology implementtation, a common phenomenon observed during the early market introduction phase of new technologies.

Acknowledgement

This project was partly funded within the framework of the research programmes "Energiesysteme der Zukunft" (www.energiesystemederzukunft.at) of the Austrian Federal Ministry for Transport, Innovation, and Technology (BMVIT), Contract No. 807742 and the EC project CROPGEN “Renewable Energy from Crops & Agrowastes” (Contract No. SES6-CT-2004-502824).

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