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Glossary

Allocation Economic term for the attribution of existing means (goods, production factors) to alternative applications (e.g., production of good A or B).

Balance of the residual load The balance of the residual load as defined below is not identical to the specified concept of the balancing energy (see definition at the end).

The residual load is usually covered by market products in hourly time frames.

The appearing short-term and often even not predictable fluctuations of generation and demand can be balanced by ancillary services (control reserve). The transmission system operators are responsible for this balance. The control reserve demand can be dimensioned by the help of probabilistic convolution programs. The demand for future scenarios can be assessed.

The balance of the residual load is the main part of our study. The market products in hourly time frames as well as the products for control reserve for shorter time frames are provided by large power plants, distributed controllable suppliers (e.g., micro- CHP), centralised and decentralised storage, the power import or load control. The balance of the residual load needs a temporal behaviour from seconds up to a seasonal range. Not all technical possibilities can be employed for the whole time frames. This study analyses the questions of which technical possibility offers which potential in which time frame, which value creation can be achieved, which regulatory and legal conditions have to be created and which environmental aspects have to be considered.

Balancing energy According to the above definitions, control energy denotes the offered energy that is used in real-time in the case of frequency-sustainment methods to achieve a power balance in the total system. In comparison, balancing energy is defined as the energy that is used for balancing the deviations between the delivery and referral programmes of the individual market participants.

In contrast to the costs of the reserve capacities, the offsetting of ex-post determined costs and revenues that depend on the use of secondary control

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DOI 10.1007/978-3-642-25157-3,

reserve and minute reserve is done in the respective balancing group in quarter hourly time frames. For the invoicing, the respective balancing groups' deviations will be metrologically collected by the balancing group manager in a defined accounting period. The pricing for the balancing energy is based on the determined costs and revenues for secondary control reserve energy and minute reserve energy for every quarter hour. The middle weighted fee as a basis for the accounting can be calculated by dividing this by the total sum of the used energy in every quarter hour. The balancing energy fee is symmetrical, which means that there is no price spread between positive and negative balancing group deviations.

Control area The control area is the smallest unit of the interconnected system, which is equipped and run with a power-frequency control. The control area is the respective area of energy support in which a transmission system operator within the context of the ENTSO-E is responsible for primary control reserve, secondary control reserve and minute reserve. Each control area is specified physically by the locations at which interchange measurement of the secondary controller is performed within the interconnected system.

Control area balance The control area balance is the sum of all deviations between the reported load schedules and the actual customer consumption and the actual supply of the power plants.

Control bloc A control bloc includes one or more control areas that work together during the power-frequency control towards other involved control blocs of the system. The guide of the control bloc has to ensure the implementation of the sum schedules of the control bloc against all different control blocs. Additionally, he has to be able to reduce or increase the frequency to its set point value after frequency drifts.

Control energy Control energy is the energy that is deployed for the compensation of power imbalances in the respective control area. Control energy correlates with the integral over time of the activated or called control reserve.

Control reserve Control reserve means the power that is reserved in the net, typically by conventional power stations, in order to guarantee a balanced power. The control reserve and its demand are divided into the different market products: Primary control reserve, secondary control reserve and minute reserve (tertiary control reserve).

The different types of control reserve are called by the respective transmission system operator in periods of up to five quarter hours.

After that time, the market participants have to compensate missing power and energy with several market activities. The transmission system operators calculate the control reserve using probabilistic techniques, which consider, for example, forecasting errors, failure probability and load noise (including the short-term noise of renewable suppliers).

The defined market products for control reserve have contractually fixed reliability and determinancy requirements. The activation has to be guaranteed in short time intervals. Due to these strict requirements it has been quite difficult to provide offers for these products from DSM, DR or virtual power plants.

Cycle With regard to energy storage systems, a cycle is defined in the study as an equivalent nominal energy throughput. A certain number of partial cycles can add up to a cycle, if the total discharged energy equals the nominal energy content of the storage system. The typical operation for most storage systems is partial cycling, however, for the economic assessment ultimately the number of times the storage system is selling its available energy to the market is of relevance and this is expressed by the number of cycles.

Demand response (DR) In principle, DR is based on the same mechanisms as DSM, except for the absence of a deterministic control option between aggregator and load. Instead, the aggregator obtains a specific load behaviour by means of incentives (such as, for example, flexible tariffs) and the loads react with a specific stochastic change in behaviour.

The information technical effort is much smaller, whereas the responsiveness is far away from the quality that is needed for ancillary services.

Demand-side management (DSM) Demand-side management indicates the optimal control of power demand or customer load for customers in the industry, in the trade or in private households. The difference to demand response is that targeted control signals are transmitted by means of communication technologies to the customers, which as far as possible (except for technical failures) react deterministically in response to that signal.

DSM is used to adjust the load during periods of limited power generation (e. g., during times of wind calms) or during periods of high demand (peak load at lunchtime). In this case this adjustment is a part of market development. The economical effects of this flexibility have to be passed on to the customers with the help of special rates. In the future, all these actions should be processed using special electronic market places (see BMWi: E-Energy). The role of the aggregators should develop in such a way that it bundles the load control and prepares new products for the electricity market.

Currently it is doubtful whether with the help of these mechanisms ancillary products such as control reserve should be aggregated and offered. The reason for this is that the communication technical control effort is extremely high and the revenue potentials due to the product design is lower than the revenue from normal trading operations, e.g., at the spot market.

In this case, electrically powered vehicles can be treated as special loads. Controllable micro- generators in private households, for example micro-CHP, can be involved in this concept whereby this concept conflates with virtual power plant utilisation.

While using DSM it is not possible to achieve a displacement of loads for several days. There is only the chance of reaching a displacement of loads in hourly time frames. In the course of the day, DSM can help to smooth the residual load and therefore to reduce the utilisation of peak load power plants.

Distribution Distribution is the economic term for the attribution of existing means (goods, production factors) to individuals or groups of individuals (e.g. households) in an economy.

Efficiency
1. A numerical value reflecting the ratio of gained outputs to applied inputs for a process.
2. The aim to realise the highest value of efficiency possible for the processes in focus.

Efficient Characterisation of a process displaying a high efficiency.

Energy-to-power ratio The energy-to-power ratio (E2P ratio) describes, for storage systems, the ratio between the installed energy capacity of a storage systems and the installed power for charging or discharging the storage systems. The unit of the E2P ratio is hours and shows directly how long the storage system can match power requirements and full power. In the basic definition, we assume a symmetric installed power for charging and discharging the storage system. In fact this is not always the case. If this is of relevance, it will be discussed explicitly.

External Costs These are the costs caused by an activity of one economic subject which has a negative or positive influence on a second economic subject, but are not accounted for in the economic decision making of the originator. Major reasons for their occurrence are missing property rights of public goods, e.g. environmental media.

Hydro storage The term “hydro storage” is used for hydropower plants with a dam to store water from natural feeders. These power plants can generate electric power on demand, but they have no pumps to absorb electric power from the grid by increasing the water level in the storage lakes.

Hydrogen storage A “hydrogen storage” system is an electricity-in/electricity-out storage system using hydrogen as the storage medium. The hydrogen is generated by electrolysis from water. Power generation occurs in larger systems from hydrogen gas turbines and in smaller system by fuel cells. The hydrogen stays at the site of generation and is not used for any other purposes.

Minute reserve/tertiary control Minute reserve replaces the secondary control reserve and, therefore, works for the restoration of the secondary control reserve band. The minute reserve from the providers is activated manually by the respective transmission system operator.

Pareto-optimum This is a societal situation in which it is not possible to increase the welfare of one individual by re-allocation of resources without decreasing the welfare of a second individual.

Plug-in hybrid Plug-in hybrid electric vehicles (PHEV) using an electrical drive train and an additional internal combustion engine (ICE). This allows the vehicle to achieve the same driving ranges as conventional cars. There are parallel hybrids, where the ICE can bring mechanical energy on the road besides the battery charging. In contrast, in serial hybrid electric vehicles the ICE is only acting as power generator at all times. This concept is often also called “vehicle with range extender”. Within this study we will not differentiate concerning parallel or serial hybrid vehicles, because from the point of view of the power grid the concepts are similar.

Power-frequency control The power-frequency control describes a control process whereby the transmission system operators can maintain the mutually agreed electrical values at the boundaries of their control areas under normal operation and in particular under fault conditions.

In this process, each transmission system operator endeavours, by means of an appropriate contribution within his own control area, to maintain both the interchange with other control areas within the agreed boundaries and the system frequency close to the set point value.

Primary control reserve An interference-induced deviation from the main frequency, for example, a power plant failure, activates power within a few seconds at every primary-regulated machine. The regulators adjust the power until a balance between power generation and consumption has been achieved. The frequency stabilises on a quasi-stationary value, which differs from the set point value because of the static (proportionality factor) proportional working primary regulators. The use of primary control reserve is controlled automatically by the frequency deviation. It operates dependent of the power control of the generation unit and has to be available at any time.

This means that power plants that offer primary control reserve have to keep this power permanent.

The primary control reserve is provided in a way of solidarity by all synchronously connected control areas inside the ENTSO-E area and it is distributed according to the regulations of the ENTSO-E to the European control areas, according to their proportion of net power generation. Splitting the European integrated network into smaller subnets (control areas) during or after a failure should ensure that a necessary primary control reverse is available in every subnet and that there are suitable transmission capacities.

Primary energy Energy content of natural resources and the environment usable for energy supply.

Primary energy storage/primary battery Energy storage systems that can be discharged only once. No recharge is possible. Examples are power generators with fossil fuels or non-rechargeable batteries such as zinc-alkaline batteries.

Pumped hydro "Pumped hydro" is used for storage systems that allow the generation of electric power from the water in the upper storage lake or the absorption of electric power from the grid by pumping water either from a river or a lower lake to the upper storage lake. The upper storage lake may have in addition natural feeders, but it can be also an artificial lake without any natural feeders.

Residual load The residual load is usually defined as the difference between the required electrical power (customer load) and the fed-in power from renewable energy sources (including heat controlled CHP). The residual load is therefore the power that still has to be covered by conventional power plants, energy storage, the power import from neighbouring control areas, current controlled CHP and load reduction.

Reserves The part of the natural (materialised) resources that can economically be mined.

Resources Means for the production of goods and services, for instance produced capital, natural capital, working hours, soil, oil, natural gas, coal, and minerals.

Secondary control reserve The secondary control reserve follows the primary control reserve. It has to be available in full, and permanent again within 5 min of activation. To achieve these targets, every participating generation unit has to be connected directly or indirectly via the main control room of the provider (e.g., merging different generators in one pool) to the power-frequency controller of the respective control area. Therefore, a centralised control system measures the present frequency drift to the set point value as well as the load flows at every substation and at every entry and exit point nearly every second.

Based on these measured values, the set point guidelines for the secondary control reserve can be calculated and afterwards transmitted online to the generation units to reduce or increase the feed-in power corresponding to the current defaults of the central power-frequency controller.

Socio-economic costs These are costs incurring to society due to not internalised external costs, for instance, an increase in cases of asthma due to decreased air quality.

Sustainability Specific concepts for maintaining societal assets in the context of ensuring a just intergenerational distribution.

Storage A storage facility in the study is equivalent to a technical system that can provide positive and/or negative control power to the grid. Therefore, all technologies beyond the classical storage systems that take up electrical energy and supply electrical energy are also considered in the study as synonyms of classical storage.

Technologically neutral Policy measures are technologically neutral if no technology is preferred or discriminated against after taking into account all market imperfections (cf. Metcalf 2009).

Tertiary control See **minute reserve**.

Type days Scaled profiles (load and feed-in profiles) used to convert the annual energy quantities into hourly time-variation curves. Each representative year thus contains 3 days (Saturday, Sunday and one working day) of each season (winter, spring, summer and autumn). Twelve typical average days within a year result from this.

Vehicles-to-grid (V2G) V2G means that, in contrast to the consideration of electrically powered vehicles as loads, it is also possible that these vehicles feed back energy into the supplying net or supply ancillary services (see control reserve). Therefore, the vehicle acts as a battery that is temporary connected to the energy network to support the network operations. The feedback of the energy requires a lot of technical safety installations in the vehicle, so that the electrically powered vehicles initially can be seen as controllable load in the case of DSM and DR.

Virtual power plants A virtual power plant is an interconnection of small and medium-sized decentralised electric power plants, such as, for example, photovoltaic systems, small hydropower plants and biogas plants, but also small wind power plants and combined heat and power plants, for offering available power plant capacity within the electricity market.

Present realisations of virtual power plants often bundle medium-sized combined heat and power plants (CHP plants) that supply building complexes with a centralised guidance and optimising system. As long as the marginal conditions of heat requirement and heat buffering are adhered to, the power generation can be controlled during the day. Therefore, the opportunity for power generating is only offered if the heat can be used or stored. As a result, only parts of the plant capacity are available as secured capacity during the year.

Several public utilities are using virtual power plants to reduce the demand for balancing energy within the balancing group.

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B. Droste-Franke et al., *Balancing Renewable Electricity*,
Ethics of Science and Technology Assessment 40,
DOI 10.1007/978-3-642-25157-3, © Springer-Verlag Berlin Heidelberg 2012

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Sauer, Universitätsprofessor Dr. rer. nat. Dirk-Uwe, born in Mannheim in 1969, studied physics at the Universität Darmstadt from 1989 to 1994. He accomplished his diploma thesis from 1992 to 1994 at the Fraunhofer Institute for Solar Energy Systems ISE in Freiburg (Breisgau) on "Modelling and simulation of systems and components of autonomous photovoltaic power supply systems". After that he worked as research scientist and senior scientist at Fraunhofer ISE until 2003, being head of the group "Storage systems" from 2000 to 2003. In parallel, from 2001 to 2003, Sauer was head of the interdisciplinary working group on "Off-grid and rural electrification" and managing director of the "Club for rural electrification".

In 2003 he received his doctorate (Dr. rer. nat.) at the Universität Ulm. The topic of his thesis was "Optimisation of the usage of lead-acid batteries in photovoltaic-hybrid systems with special emphasis on battery ageing". In October 2003 Sauer was appointed for junior-professorship and in 2009 for university professorship at the RWTH Aachen University for "Electrochemical energy conversion and storage systems" (Faculty for Electrical Engineering and Information Technology). His main areas of work pertain to electrochemical energy storage (batteries) and autonomous power supply systems.

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He studied law (and economics) at the Universities of Marburg and Freiburg (Germany), holds a doctor in law from the University of Freiburg (Germany) (Dr. iur.), worked as a junior lawyer in state and federal ministries as well as in the City attorney´s office of San Francisco and habilitated at the University of Hamburg (Germany).

Schreurs, Professor Miranda, Ph.D., became Director of the Environmental Policy Research Center and Professor of Comparative Politics at the Freie Universität Berlin in 2007. Prior to this she was an Associate Professor of Comparative Politics at the University of Maryland, College Park. Her Ph.D. is from the University of Michigan (1996). In 2008, she was appointed as a member of the Advisory Council on the Environment, a consultative committee of the German Federal government. In 2011, she became chair of the European Environment and Sustainable Development Advisory Councils, a network of approximately 25 advisory councils across Europe. In this year, she was also appointed by Chancellor Angela Merkel to the Ethic Commission on a Safe Energy Supply, charged with advising the German government with advice regarding energy questions in the post-Fukushima era. She was the 2009–2010 Fulbright New Century Scholar Program's Distinguished Leader and in this capacity co-ordinated the programs activities on the Role of the University as Knowledge Center and Innovation Driver.

Ziesemer, Professor Dr. rer. pol. Thomas, has been an Associate Professor of Economics since December 1996. He studied economics at the Universities of Kiel (1974–1975) and Regensburg (1975–1978) in Germany. From 1982 to 1989 he was employed at the University of Regensburg, where he completed his doctoral dissertation on Economic Theory of Underdevelopment in 1985. Since December of 1989, he has been successively an Assistant Professor of International Economics, Associate Professor of Microeconomics (1994–97), Maastricht University, and is currently Associate Professor of Economics all at the School of Business and Economics, Maastricht University. In November 1996 he received his "Habilitation" from the Free University Berlin in 1996. His fields of interest include Development, International and Environmental Economics, Growth, and Technical Change.

Appendix

The Relation Between Emission- and Labour-Saving Technical Change in an Optimal Growth Model with Emission Reduction Constraints

The question treated here is how technical change shifts from being labour-augmenting to energy-saving, when these two types of technical change are both endogenous. This question is relevant when emission reductions are enforced and make energy use more expensive relative to labour. Then, the more expensive use of energy and emissions provide an incentive to invest in energy-saving or emission-reducing technical change, which implies a lower relative incentive to invest in labour-saving technical change. What is unpredictable, without formal modelling, is how the difference between the two rates of technical change will develop.

Optimal Growth

In order to tackle this problem, we set up an optimal growth model in which energy-saving and labour-augmenting technical change are both endogenous, whereas the use of emissions, E, and labour are growing at exogenous rates. For labour, this is the growth of the labour force, N, multiplied by an exogenous, constant rate of employment, $(1-u)$, resulting in $(1-u)N = L$.

The Model

We do not consider explicitly a market economy but rather formulate an optimal growth model, where a central planner maximises infinite horizon utility, given an exogenous fall in the rate of emissions, which he uses as a restriction taken from climate models. We specify the rest of the model as simply as possible in order to make the issue tractable.

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Ethics of Science and Technology Assessment 40,
DOI 10.1007/978-3-642-25157-3, © Springer-Verlag Berlin Heidelberg 2012

Technologies

Output Y is produced using two factors, labour L growing at an exogenous and constant non-negative rate and emissions, E, growing at a negative rate. For both there is a technology level A_i, $i = E, L$.

$$Y = [\alpha(A_L L)^\rho + (1-\alpha)(A_E E)^\rho]^{1/\rho}, \tag{1}$$

The technology levels can be changed by employment of researchers of which the economy has an endowment, H, which can be employed in production functions F and G, where each prime indicates a derivative. The first derivatives are assumed to be positive and the second negative.

$$\dot{A}_E = A_E F(H_E), F'>0, F''<0 \tag{2}$$

$$\dot{A}_L = A_L G(H_L), G'>0, G''<0 \tag{3}$$

Preferences

Households are assumed to have preferences for any moment in time $u(c)-v(E)$, discounted at rate δ, for all future time periods τ from the present t to an infinite horizon.

$$\begin{aligned} U &= \int_t^\infty e^{-\delta(\tau-t)}[u(c)-v(E)]d\tau; with \quad u = \frac{1}{1-\sigma}c^{1-\sigma}, \quad implying \\ u' &= c^{-\sigma}, u'' = -\sigma c^{-\sigma-1}; v'<0 \end{aligned} \tag{4}$$

Endowments

Factor endowments are the initial values of labour, L, human capital, H and productivity A_i:

$$A_E(0), A_L(0), L(0), H(0).$$

Constraints

The resource constraints can be formulated as follows:

$$\mathrm{H} = \mathrm{H}_\mathrm{L} + \mathrm{H}_\mathrm{E} \tag{5}$$

$$\hat{E}<0;\ \hat{L} \geq 0 \tag{6}$$

H is assumed to be constant. Otherwise a slight reformulation would be required in order to avoid the scale effects problem (see von Weizsäcker 1969; Jones 1999)

Hamiltonian

Applying Pontryagin's maximum principle we formulate the Hamiltonian as

$$U = \frac{1}{1-\sigma} c^{1-\sigma} L + \lambda \{ [\alpha (A_L L)^\rho + (1-\alpha)(A_E E)^\rho]^{1/\rho} - cL \} + \mu A_E F(H_E) + v A_L G \times (H - H_E)$$

The first order conditions are

$$c:\ \ c^{-\sigma} - \lambda = 0 \tag{7}$$

$$H_E:\ \mu A_E F'(H_E) + v A_L G'(H - H_E)(-1) = 0 \tag{8}$$

$$\begin{aligned} A_E\ :& -\frac{\partial U}{\partial A_E} = \dot{\mu} - \delta\mu = \\ & - \lambda \frac{1}{\rho} [\alpha (A_L L)^\rho + (1-\alpha)(A_E E)^\rho]^{\frac{1}{\rho}-1} \rho (1-\alpha)(A_E E)^{\rho-1} E - \mu F(H_E) \end{aligned} \tag{9}$$

$$\begin{aligned} \mathrm{A}_\mathrm{L}:& -\frac{\partial U}{\partial A_L} = \dot{v} - \delta v \\ & = -\lambda \frac{1}{\rho} [\alpha (A_L L)^\rho + (1-\alpha)(A_E E)^\rho]^{\frac{1}{\rho}-1} \rho \alpha (A_L L)^{\rho-1} L - v G(H - H_E) \end{aligned} \tag{10}$$

Using the production function and the fact that cL equals output, (9) and (10) can be reformulated as

$$\dot{\mu} - \delta\mu = -\lambda [cL]^{1-\rho} (1-\alpha)(A_E E)^{\rho-1} E - \mu F(H_E) \tag{9'}$$

$$\dot{v} - \delta v = -\lambda [cL]^{1-\rho} \alpha (A_L L)^{\rho-1} L - v G(H - H_E) \tag{10'}$$

A steady state is defined as a constant allocation of the human capital variables and constant growth rates for each variable. Dividing the last two equations by μ and ν respectively yields

$$\dot{\mu}/\mu - \delta = -(\lambda/\mu)[cL]^{1-\rho}(1-\alpha)(A_E E)^{\rho-1}E - F(H_E) \tag{9''}$$

$$\dot{v}/v - \delta = -(\lambda/v)[cL]^{1-\rho}\alpha(A_L L)^{\rho-1}L - G(H - H_E) \tag{10''}$$

In a steady state we would have a constant growth rate of μ, ν, A_L, A_E. From the first-order condition for H-terms, (8), it follows that

$$\hat{\mu} + \hat{A}_E = \hat{v} + \hat{A}_L \tag{8'}$$

To prepare the use of this, the differential equations for μ and ν can be rewritten as

$$\dot{\mu}/\mu + F(H_E) = \delta - (\lambda/\mu)[cL]^{1-\rho}(1-\alpha)(A_E E)^{\rho-1}E \tag{9'''}$$

$$\dot{v}/v + G(H - H_E) = \delta - (\lambda/v)[cL]^{1-\rho}\alpha(A_L L)^{\rho-1}L \tag{10'''}$$

Equality of the left-hand sides implies equality of the right-hand side terms and therefore

$$(\lambda/\mu)[cL]^{1-\rho}(1-\alpha)(A_E E)^{\rho-1}E = (\lambda/v)[cL]^{1-\rho}\alpha(A_L L)^{\rho-1}L \tag{11}$$

Cancellation of identical terms yields

$$(1/\mu)(1-\alpha)(A_E E)^{\rho-1}E = (1/v)\alpha(A_L L)^{\rho-1}L \tag{11'}$$

Rewriting (11′) in terms of growth rates yields

$$-\mu + (\rho - 1)\hat{A}_E + \rho\hat{E} = -\hat{v} + (\rho - 1)\hat{A}_L + \rho\hat{L} \tag{11''}$$

Using (8′) allows cancellation to get

$$\hat{A}_E + \hat{E} = \hat{A}_L + \hat{L} = \hat{Y} \tag{11'''}$$

With exogenous growth of *E* and *L* it follows that

$$\hat{A}_E - \hat{A}_L = \hat{L} - \hat{E} \tag{11^{\text{iv}}}$$

The growth rate in efficiency units is equal for *E* and *L* according to (11’’’), or the growth rate difference between *L* and *E* will be equal to that of their rates of technical change as in (11^{iv}). If E would have positive growth as the GDP had in the past, given that of L, the left-hand side of (11^{iv}) would be much smaller. A special case that is familiar to the economist from growth theory would be that the first term is zero, the second is -2% and so is the right-hand side: labour-productivity and GDP per capita growth at a rate of 2%. If, however, labour grows as the rate of population in the OECD at 0.6% and E grows at -2% as climate models seem to recommend, than the right-hand side of (11^{iv}) is 2.6% and therefore emission-saving technical progress will be 2.6% larger than labour augmenting technical change.

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