18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

GIS based model to optimize the utilization of renewable energy carriers and related energy flows

Biberacher, M. [1] **and Gadocha, S.** [1]

[1] *Research Studios Austria Forschungsgesellschaft mbH, Studio iSPACE, Salzburg, Austria*
Email: markus.biberacher@researchstudio.at

Abstract: A significant part of final energy consumption is demand for space heating. This demand is mainly met by fossil fuels. Given the challenge of climate change and question marks over energy security and import dependency on fossil fuels, improvements in energy efficiency and greater use of renewable energy may be important policy considerations.

The paper presents a modelling approach for the optimization of the fulfilment of the heating demand within a defined region of interest, favouring renewable energy carriers - with a particular focus on spatial differentiation. The modelling approach that is presented handles information on geographically disaggregated data describing renewable energy potentials (biomass, solar energy, geothermal energy, ambient heat) on the one hand and geographically disaggregated information on the heating demand on the other hand. This spatial balance is the basis for modelling an optimum spatial utilization of identified renewable energy resources to satisfy the heating demand with respect to the objective function of the model, which is defined as highest economic efficiency with respect to greenhouse gas emissions constraints in the region. To take into account the spatial relevance of the single elements of the energy system in an appropriate way, all relevant spatial data are disaggregated to a consistent spatial resolution. This includes the energy potentials, the demand structure as well as some infrastructure data. The region of interest is segmented into a collection of raster cells, which present the smallest spatial unit in the model. The smallest size of raster cells is 250 m x 250 m.

The general model framework within this approach consists of three parts:

- **The potential model** – includes separate models to estimate the potential of individual renewable energy carriers (biomass, solar energy, geothermal energy, ambient heat) in a spatially disaggregated way with their specific characteristics. These separate models are integrated into the overall potential model.
- **The demand model** – illustrates the spatially disaggregated heating demand, expressed as heating degree days. This is the basis for the estimation of the effective demand in relation to the insulation standard of buildings.
- **The dynamic fulfilment model** – is used to derive an optimized setup of the energy system for the fulfilment of the heating demand. For the generation of various scenarios a distinction is made between fixed parameters defined by the system (present situation) and variable parameters (e.g. future costs). The variable parameters (insulation standards, domestic fuel type, natural gas and district heating grid, fuelling of power plants and use of renewable energies) are defined differently for the development of the scenarios. Depending on these definitions, a sensitivity analysis can be carried out. The model is implemented as a linear optimization model realized in the modelling language GAMS.

The use of scenario analysis allows the testing for key sensitivities in the model. These outcomes may have important policy implications or provide strategic information to stakeholders.

Keywords: *Geographic Information System (GIS), renewable energy, spatial modelling, energy demand*

1. INTRODUCTION AND OBJECTIVE

In Europe more than 50 % of final energy consumption is used for space heating. This demand is principally met by the combustion of fossil fuels. Recently, climate change and energy security have moved to the top of the political agenda. The natural gas crisis between Russia and the Ukraine that affected other European countries provides a prescient example of energy security issues. A reliable, secure, efficient and environmentally sound energy supply is essential for a sustainable provision of goods and services. The long-term impacts of CO2 emissions in relation to global warming and the challenge to meet the obligations of the Kyoto protocol have increased awareness of energy supply issues, highlighting the need for an increased use of renewable energy. Due to the above issues the need for an enhanced use of renewable energy carriers is evident. The modelling approach presented here aims at a spatial optimization of the fulfilment of the heating demand within a predefined region of interest with emphasis on the use of renewable energy carriers. For the model region the district level is assumed and the spatial disaggregation within the model region goes down to single raster grid cells of a 250m size. A linear optimization model is implemented to optimize the satisfaction of the heat demand preferably using renewable energy carriers for the whole region. The objective of the model is the reduction of regional greenhouse gas emissions at the lowest possible economic cost.

2. THE MODEL FRAMEWORK

The spatial model for the optimization of the fulfilment of the heating demand aims at a

- spatially disaggregated illustration of the heating demand
- spatially disaggregated illustration of renewable energy potentials
- derivation of individual scenarios regarding the fulfilment of demand

One focus of the model is the integration of spatial differences within the demand and supply structures as well as the integration of the spatial availability of infrastructure. The emphasis of the model is on the derivation of an optimized setup of the whole system for the demand fulfilment - depending on dynamic input assumptions.

The share of utilized technologies to satisfy the heating demand with respect to different scenario depending greenhouse gas emission thresholds at the lowest possible economic cost will be derived for each single location.

The spatial dimension of the model is important as location matters in the delivery of alternative energy solutions.

2.1. Spatial disaggregation

To take into account the spatial relevance of the single elements of the energy system in an appropriate way, all spatially relevant data are disaggregated to a consistent spatial resolution. This includes the energy potentials, the demand structure for heating as well as the relevant data on infrastructure.

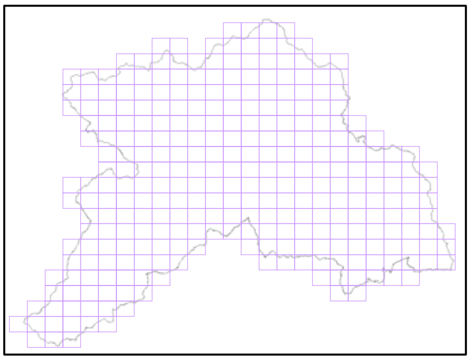

Figure 1: Segmentation of testing region (NOT real segmentation, only representative)

Therefore, the region of interest is segmented into single raster cells, which are considered in the model as the smallest spatial unit (Biberacher et al., 2008). These smallest spatial units are geographical rectangles which are decoupled from political units. A possible segmentation is shown in Figure 2. The size of these rectangles is chosen as a compromise between effort in computing power and the significance of a high spatial resolution. It is assumed that neighbouring cells are connected via existing and future grid based infrastructure (district heat, natural gas grid, street network). Boundary cells are considered as start and end points for grid based infrastructure.

For the single raster cells all relevant energy related information is provided, including:

- current heat demand situation for every raster cell

- renewable energy potentials within every raster cell
- specific costs for the reduction of the heat demand within the single cells (e.g. due to enhancement of insulation standard of buildings)
- specific costs for the different technology options to satisfy the energy demand within the single raster cells
- specific costs for infrastructure (district heating, natural gas grid)
- currently used energy carriers for the satisfaction of the heating demand
    - oil
    - natural gas
    - district heating
    - biomass
    - solar
    - geothermal energy
    - ambient heat

2.2. Demand fulfilment model

The objective function and therefore the criteria to evaluate a setup of the energy system in the region of interest is a reduction of greenhouse gas emissions at the lowest economic cost. Figure 3 shows the design of the dynamic demand fulfilment model.

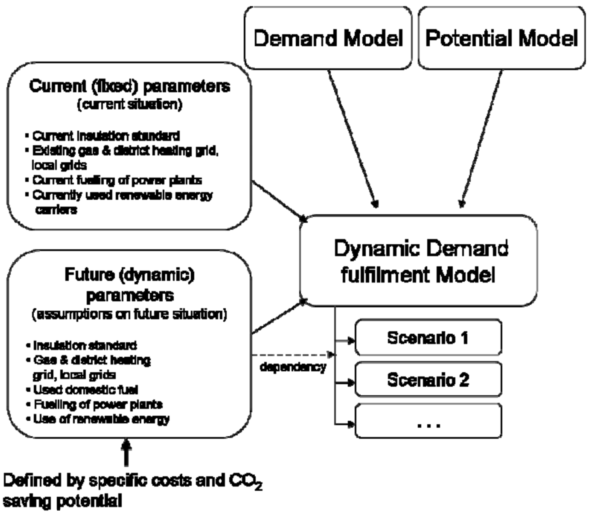

Figure 2: Overview of the demand fulfillment model

Based on the objective function an individual optimized setup of the energy system can be derived. The setup shows the following information for every individual raster cell, based on the parameterized initial state:

- Share of heat demand satisfaction:
    - by oil
    - by natural gas
    - by district heating
    - by biomass
    - by solar
    - by geothermal
- infrastructure
- reduction of energy demand due to an enhancement of the insulation standard

The raster approach with a flexible chosen raster size allows a maximum flexibility in the selection of a suitable compromise between attention to the detail of the system description and the effort of the modelling process.

For the generation of various demand fulfilment scenarios a distinction is made between current parameters (fixed) defined by the actual system and future (dynamic) parameters, like assumptions of a future development of costs and demand. The variable parameters are defined differently for the development of the different scenarios. Depending on the parameters, different decisions regarding an optimum system setup and therefore different scenarios result. The use of scenario analysis allows the testing of key sensitivities in the model.

Figure 3 shows the relevant input parameters for the demand fulfilment model (left hand side) and the variables considered to be optimized in the linear optimisation model (right hand side). Constraints in terms of maximum availability on the potential side as well as in terms of energy demand are delivered by especially devoted potential and demand models.

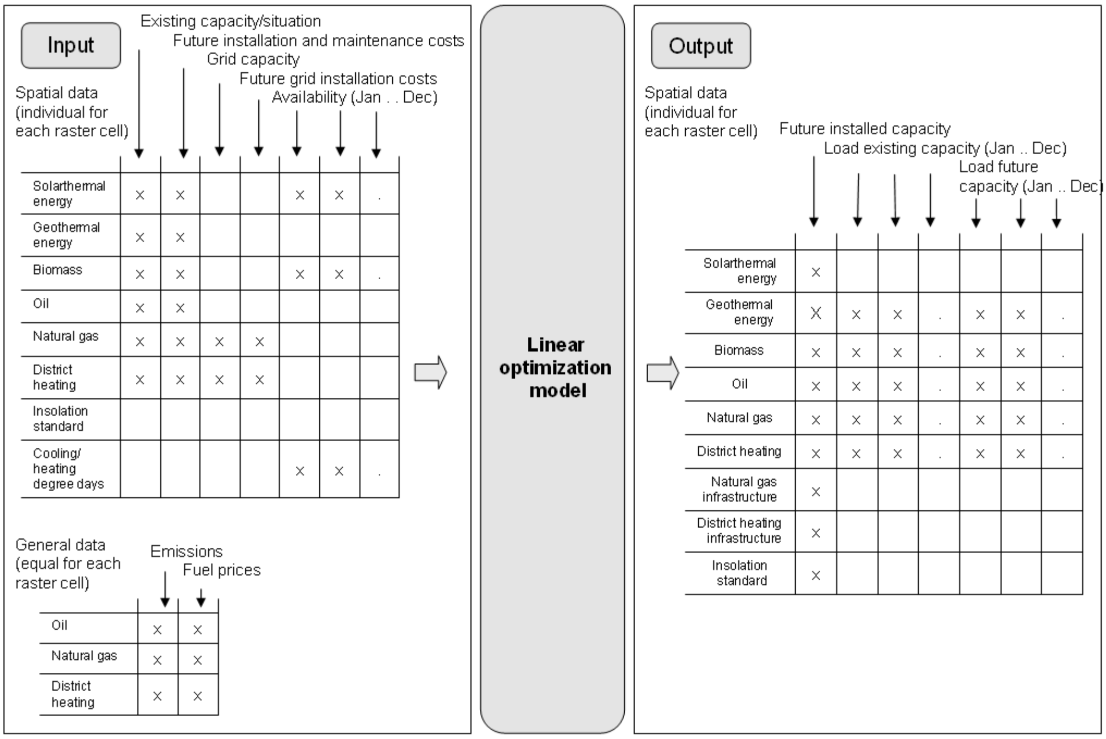

Figure 3: Variables and Parameters of the spatial fulfilment of demand model for different energy carriers

The demand fulfilment model can be described with the following equations (symbols are defined in Table 1):

Constraints:

The infrastructure load can never exceed the installed capacity:

$$0 \leq Ex_{s,x,y} - \boldsymbol{Lp}_{s,t,x,y} \qquad \text{for all } s, t, x, y \qquad (1)$$

$$0 \leq \boldsymbol{I}_{s,x,y} - \boldsymbol{Lf}_{s,t,x,y} \qquad \text{for all } s, t, x, y \qquad (2)$$

Infrastructure load must satisfy the demand:

$$0 \leq \boldsymbol{\Sigma}_s (\boldsymbol{Lp}_{s,t,x,y} - \boldsymbol{Lf}_{s,t,x,y}) + BRequ_{t,x,y} * (UVp_{x,y}, -\boldsymbol{U}_{x,y}) \qquad \text{for all } t, x, y \qquad (3)$$

Availability of supply technology *b* restricts infrastructure load:

$$0 \leq AviB_{b,t,x,y} * \boldsymbol{I}_{s,x,y} - \boldsymbol{Lf}_{s,t,x,y} \qquad \text{for all } t, x, y \qquad (4)$$

$$0 \leq AviB_{b,t,x,y} * Ex_{s,x,y} - \boldsymbol{Lp}_{s,t,x,y} \qquad \text{for all } t, x, y \qquad (5)$$

Emissions must be below a set threshold:

$$0 \leq Emi - \boldsymbol{\Sigma}_{s,t,x,y} (OpEmi_s * \boldsymbol{Lp}_{s,t,x,y} + OfEmi_s * \boldsymbol{Lf}_{s,t,x,y}) \qquad \text{for all } t, x, y \qquad (6)$$

Installations of grid based technologies must be supported by the grid connection capacity:

$$0 \leq ExG_{g,x,y} + \boldsymbol{G}_{g,x,y} - Ex_{g,x,y} - \boldsymbol{I}_{g,x,y} \qquad \text{for all } g, x, y \qquad (7)$$

The sum of connection capacities of grid infrastructure to neighbouring raster cells have to be lower or equal than the capacity in the considered raster cell:

$$0 \leq ExG_{g,x,y} + \boldsymbol{G}_{g,x,y} - \boldsymbol{\Sigma}_n \boldsymbol{GC}_{n,g,x,y} \quad \text{for all } g, x, y \quad (8)$$

The sum of connection capacities of grid infrastructure from neighbouring raster cells to the considered raster cell has to be higher or equal than the capacity in the considered raster cell minus potential plant capacities:

$$0 \geq ExG_{g,x,y} + \boldsymbol{G}_{g,x,y} - ExPG_{g,x,y} - \boldsymbol{PG}_{g,x,y} - \boldsymbol{GC}_{1,g,x-1,y} - \boldsymbol{GC}_{2,g,x+1,y} - \boldsymbol{GC}_{3,g,x-1,y-1} - \boldsymbol{GC}_{4,g,x+1,y-1} - \boldsymbol{GC}_{5,g,x,y-1} - \boldsymbol{GC}_{6,g,x,y+1} - \boldsymbol{GC}_{7,g,x-1,y+1} - \boldsymbol{GC}_{8,g,x+1,y+1} \quad \text{for all } g, x, y \quad (9)$$

Objective function:

The objective of the model will be the overall system cost:

$$\text{Minimize} \quad \boldsymbol{\Sigma}_{s,t,x,y} (\boldsymbol{Lp}_{s,t,x,y} * Op_{s,x,y} + \boldsymbol{Lf}_{s,t,x,y} * Of_{s,x,y}) + \boldsymbol{\Sigma}_{s,x,y} (C_{s,x,y} * \boldsymbol{I}_{s,x,y}) + \boldsymbol{\Sigma}_{g,x,y} (Cg_{s,x,y} * \boldsymbol{G}_{g,x,y}) + \boldsymbol{\Sigma}_{g,x,y} (CPg_{s,x,y} * \boldsymbol{PG}_{g,x,y}) + \boldsymbol{\Sigma}_{g,x,y} (CUVp_{x,y} * \boldsymbol{U}_{x,y}) \quad (10)$$

Table 1. Indices used in the equations

Indices:		Variables at each cell *x,y*:	
s:	Energy supply technology	$Lp_{s,t,x,y}$:	Load of present infrastructure for energy supply technology *s* in time step *t*
t:	Time step	$Lf_{s,t,x,y}$:	Load of new infrastructure for energy supply technology *s* in time step *t*
x:	x coordinate index of raster cell	$I_{s,x,y}$:	Capacity of new infrastructure related to buildings for energy supply technology *s*
y:	y coordinate index of raster cell	$G_{g,x,y}$:	Capacity of new grid infrastructure for technology *g*
g:	Grid based energy supply technology (subset of *s*)	$GC_{n,g,x,y}$:	Connection capacity with neighbouring cell *n,x,y*
b:	Availability of supply technologies (subset of *s*)	$PG_{g,x,y}$:	Capacity of new generating plant or supply point infrastructure for grid based energy supply technology *g*
n:	neighbouring raster cells (1 .. 8) to actual considered raster cell	$U_{x,y}$:	Difference in insulation standard for buildings due to future adaptations

Input data :			
$Op_{s,x,y}$:	Operation and maintenance costs for existing infrastructure installations for energy supply technology *s* in cell *x,y*	$AviB_{b,t,x,y}$:	Availability for supply technology *b* in timestep *t* in cell *x,y*
$Of_{s,x,y}$:	Operation and maintenance costs for new infrastructure installations for energy supply technology *s* in cell *x,y*	$BRequ_{t,x,y}$:	Heating degree days in timestep *t* multiplied by living space in cell *x,y*
$Ex_{s,x,y}$	Capacity of existing infrastructure installations for energy supply technology *s* in cell *x,y*	$UVp_{x,y}$:	Current averaged insulation standard for buildings in cell *x,y*
$ExG_{g,x,y}$:	Capacity of existing grid infrastructure for grid based energy supply technology *g* in cell *x,y*	$CUVp_{x,y}$:	Annualy discounted installation costs for adaptations in insulation standard in cell *x,y*
$ExPG_{g,x,y}$:	Capacity of existing plant or supply point infrastructure installations for grid based energy supply technology *g* in cell *x,y*	$OpEmi_s$:	Emission intensity of present technology *s*
$C_{s,x,y}$:	Annually discounted installation costs for new infrastructure related to buildings in technology *s* in cell *x,y*	$OfEmi_s$:	Emission intensity of future technology *s*
$Cg_{g,x,y}$:	Annualy discounted installation costs for new grid infrastructure based technology *g* in cell *x,y*	*Emi:*	Emission threshold for model region
$CPg_{g,x,y}$:	Annualy discounted installation costs for plant (source) adaptations in grid based technology *g* in cell *x,y*		

The output of the spatial demand fulfilment model are scenarios showing the optimal setup for the satisfaction of the heating demand in every raster cell of the grid by the different energy carriers (biomass, solar, geothermal, ambient heat, oil, natural gas, district heating) and optimal energy efficiency enhancements (e.g. insulation measures), given some set of parameters.

The model framework combines a GeoDatabase (geographic database), administered in ArcGIS, and an optimisation model, implemented with the modelling language GAMS. The optimisation model itself is a linear optimization model. An interface has been implemented to connect the model to common GIS software (Biberacher, 2007).

2.3. Potential model

The cumulative potential model consists of the different spatial models for the individual renewable energy carriers that estimate the theoretical, technical and reduced technical potential for every raster cell. The estimation of the potentials is carried out by a top-down approach.

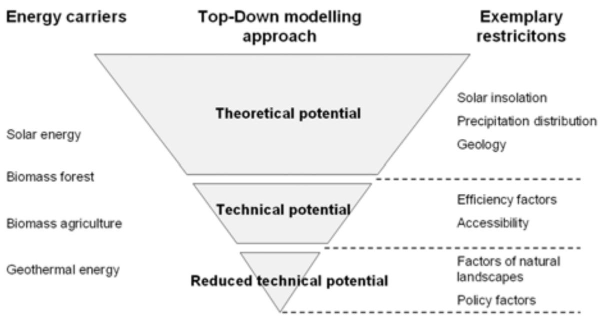

Figure 4: Top-down approach

In a first step the theoretical potential is modelled in the sense of the specific physically available potential for a certain region and a certain period (Kaltschmitt et al., 2003). This potential is then reduced by technical restrictions to the technical potential (e.g. efficiency factors) and by the integration of further limitations to a reduced technical potential (Prinz et al. 2009). The different levels of potential are estimated in a spatially disaggregated way for every single raster cell. The top-down approach is shown in Figure 4.

An overview of the cumulative potential model is given in Figure 5. The sub-models for the single renewable energy carriers are single stand-alone models. Each renewable energy carrier is treated in an individual model with focus on the constraints restricting the potential.

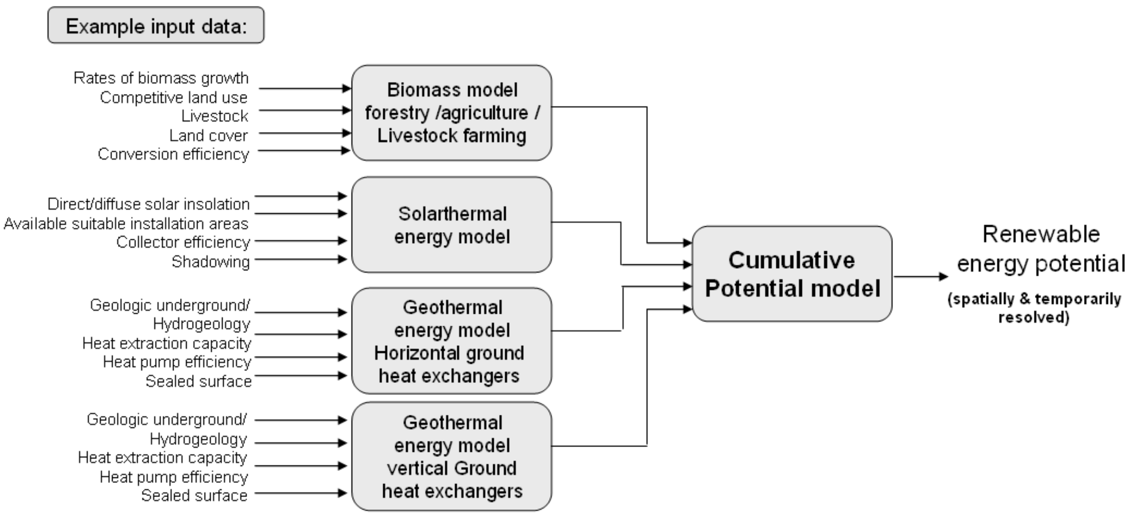

Figure 5: Potential model

2.4. Demand model

The emphasis of the demand model lies on the spatially disaggregated illustration of the heating demand – linked to relevant living space. Different parameters influence the heating demand, such as:

- Climatic factors
- Insulation standards

- Passive solar gains of buildings
- Transmission values of buildings
- Internal gains of buildings (e.g. rejected heat of electric devices or people)
- Consumer behaviour (Desired inside temperature)

The illustration of the spatially disaggregated heating demand, expressed as heating degree days (on an average month basis), builds the basis for the derivation of the estimation of the effective heat demand as a function of the insulation standard.

3. SUMMARY AND CONCLUSION

With the dynamic demand fulfilment model the derivation of scenarios is enabled, based on different parameters (insulation standard, domestic fuel use, natural gas and district heating grid or local heat network availability). Each scenario will present an optimum setup of the whole heat energy system to satisfy the heat demand within the defined region of interest based on the respective specification of the parameters used in the scenario. So far the theoretical framework for the scenario generation has been developed. The utilisation of the dynamic fulfilment of demand model for a testing region is still in progress.

By the analysis of the scenarios derived from the dynamic variation of the parameters within the fulfilment of demand model a sensitivity analysis regarding causal connections with the development of an optimum heat energy system is enabled. The spatial reference of the relevant parameters regarding the heating energy system has a high significance within the model because, with the precise localisation and visualisation of spatial conditions, future measures for the adaption of the whole energy system can be derived. The outcomes of the sensitivity analysis can therefore be used as a basis of decision making and the derivation of adequate measures regarding a future adaptation of the heat energy system within the area of interest.

REFERENCES

Biberacher, M. (2007), Modelling and optimization of future energy systems using spatial and temporal mehtods. VDM Verlag, ISBN 978-3836424356, Germany.

Biberacher, M., Gadocha, S., and Zocher, D., (2008), GIS based model to optimize possible self sustaining regions in the context of a renewable energy supply; In: Proceedings of the iEMSs Fourth Biennial Meeting: International Congress on Environmental Modelling and Software (iEMSs 2008). International Environmental Modelling and Software Society, Barcelona, Catalonia, July 2008. ISBN: 978-84-7653-074-0

Kaltschmitt, M., Wiese, A., and Streicher, W. (Hrsg.), (2003), Erneuerbare Energien. Systemtechnik, Wirtschaftlichkeit, Umweltaspekte. Berlin.

Prinz, T., Biberacher, M., Gadocha, S., Mittlböck, M., Schardinger, I., Zocher, D., Riedler, W., Strasser, H., Fackler, A., Dorfinger, N., Obersteiner, M., (2009), Energie und Raumentwicklung – Darstellung der Potenziale erneuerbarer Energie. Österreichische Raumordnungskonferenz (ÖROK) (Hrsg.), Wien, in press.