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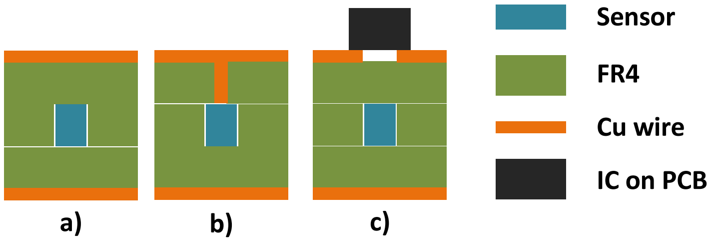

Featured article:

Comparison of different energy harvesting solutions for printed circuit board production

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Sustainable energy infrastructure siting: an agent based approach

可持续能源基础设施选址:采用基于个体的方法

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Abstract - **Technical, environment, social, economic and political constraints are critical barriers to the development of new renewable energy supplies. This paper is an agent-based, predictive analytics model of energy siting policy in the techno-social space that simulates how competing interests shape siting outcomes to identify the beneficial policy for sustainable energy infrastructure. Using a high voltage transmission line as a case study, we integrate project engineering and institutional factors with GIS data on land use attributes and US Census residential demographics. We focus on modeling citizen attitudinal, Community Based Organization (CBO) emergence and behavioral diffusion of support and opposition with Bilateral Shapley Values from cooperative game theory. We also simulate the competitive policy process and interaction between citizens, CBOs and regulatory, utility and governmental stakeholders using a non-cooperative game theory. In addition, our model simulates the complexity of infrastructure siting by fusing citizen attitude and behavior diffusion, stakeholder bargaining and regulatory decision-making. We find CBO formation, utility message and NGO messaging have a positive impact on citizen comments submitted as a part of the Environmental Impact Statement process, while project need and procedure have a negative impact. As citizens communicate and exchange political opinions across greater distances with more neighbors, less CBOs form but those that do are more effective, increasing the number of messages citizens send. Our results also indicate that despite the money spent on assessing the engineering aspects of major infrastructure projects, citizen participation and political power can be more important to stakeholder bargaining outcomes than the level of local disruption that project causes.**

Keywords –**infrastructure siting, game theory, agent-based model, Bilateral Shapely Values, community-based organization**

摘要－技术、环境、社会、经济和政治约束是新的可再生能源供应发展的主要障碍。本文介绍了一个基于个体的预测分析模型，重点分析在科技社会空间中的能源选址政策，模拟利益冲突如何影响选址的结果来确定可持续发展能源基础设施的有理政策。使用高压输电线路为例，我们结合项目工程和制度因素，并采用土地使用属性的 **GIS** 数据和美国住宅人口普查数据。使用夏普利值及合作博弈理论，我们的模型专注于公民态度，基于社区的组织(**CBO**)的出现，和支持与反对的行为扩散。使用非合作博弈理论，我们还模拟市民、当地监管部门、公用和政府利益相关者之间的竞争政策过程和互动。此外，我们的模型还融合了公民的态度和行为扩散，利益相关者的交涉，和监管部门的决策来模拟基础设施选址的复杂性。我们发现**CBO**的形成、公共部门信息和非政府组织信息对环境影响声明过程中的公民的信息提交产生积极影响，而项目需要和过程对公民信息提交产生负面影响。随着公民沟通和交流的政治观点跨越更大的距离并联系更多的邻居，**CBO**的数量减少但是以更有效的形式呈现，增加公民提交信息的数量。我们的研究结果还表明，尽管有大量的钱花在评估重大基础设施项目的工程方面，相较于项目对当地造成的破坏，公民参与和政治力量对于影响利益相关者的交涉结果可有更大的作用。

关键词－基础设施选址，博弈论，个体为本模型，夏普利值，基于社区的组织

I. INTRODUCTION

Technical, environment, social, economic and political constraints are critical barriers to the development of new renewable energy supplies. This paper reconceptualizes how we “get to yes” by encouraging public participation and shifting opposition to the “other” side’s proposals. In this agent-based model of energy siting policy, we focus on how competing interests shape siting outcomes and identify actionable strategies to help build energy infrastructure in a more timely and less conflictual manner that current processes typically allow.

In this article, we investigate the effect of public participation on agency decision-making. Public managers must balance citizen demands, business interests, and the public interest, conceived of as public policy goals. While the relative influence of citizens versus interest groups in administrative decision-making is one of the enduring questions in political science and public administration, investigations of relative citizen influence often rely on case-based methods that typically focus on macro-level issues such as institutional rules, problem severity, as well as the attributes of the decision-making outcome. Yet, to estimate the independent effects of public participation, the other micro-level contextual variables must be, or are assumed to be, held constant. As Collins [14] states, if research were to include the effect of the complex interactions between individual actors, then the development of generalizable theories would be limited by our scholarly resources to investigate the population of cases. Our computational modeling approach compliments, rather than substitutes for, empirical research and literature reviews, and can offer a method for generating novel theoretical insights into citizen influence [13].

Using a high voltage transmission line as a case study, we integrate project engineering and institutional factors with GIS data on land use attributes and US Census residential demographics. We focus on modeling citizen attitudinal, Community Based Organization (CBO) emergence and behavioral diffusion of support and opposition with Bilateral Shapley Values from cooperative game theory. We also simulate the competitive policy process and interaction between citizens, CBOs and regulatory, utility and governmental stakeholders using a non-cooperative game theory. In addition, our model explores the complexity of infrastructure siting by fusing citizen attitude and behavior diffusion, stakeholder bargaining and regulatory decision-making.

Our simulation results provide strategic advice to users about how to reach consensus on sustainable energy infrastructure siting issue given its dynamics, offer insights about policy levers, issue linkage strategies, bargaining positions, scenarios analysis to explore key uncertainties, and can identify equitable solutions supported by communities.

II. Literature

Sustainable energy infrastructure development can be seen as a mixed motive social dilemma where public goods provision is in conflict with private interests. There have been a lot of attentions paid to environmental sustainability and new regulatory rules, have so utilities, stakeholders, and government officials are under the pressure to find new and creative solutions to the complex problems of sustainable resource use. We focus on the Environmental Impact Assessment (EIA) decision-making processes because they are common and the EIA process structures agency decisions. EIA processes require and notice and comment period like the Administrative Procedures Act. [1]EIA's involve analyzing the likely environmental and social impacts of a project in a multidisciplinary fashion, presenting the information to the public and decision makers, and taking public and stakeholder comments into account in the final decision. The siting of an energy project usually begins with the project sponsor developing a detailed and substantial review of social and environmental impacts, typically prepared by the project proponent, which gives it significant advantages in determining the alternatives and the initial assessment of costs and benefits of the project design. The EIA process involves public notification of the project proposal, public involvement in scoping, preparation of a draft EIA, public review and comment on the draft EIA, and the preparation of a final EIA that takes public comments into account [31].

There is substantial evidence in the planning and political science literature that ensuring robust public participation and making use of collaborative planning approaches can significantly reduce conflict [8, 9]. A study of planning in the Great Lakes region find that an open and fair participatory process is associated with greater trust and better policy outcomes. Many public participation practices reduce conflict and develop accountability [8]. Increased public participation can include building trust, developing "buy-in", provide objectively superior decisions, and lead to a more healthy democratic society [8].

The second type of theoretical and empirical support for the model development is industry impact in administrative decisions. Although stakeholder participation in general has elicited great expectations for power sharing among diverse interests and individuals, public consultation can just legitimize decisions that have already been made [20]. Other researchers have been concerned that stakeholder processes simply reproduce the power relations already present in a jurisdiction [6][16]. Public participation has been conceived as a means to check power of the state and market [44].

The third body of literature that contributes to the model comes from lobbying and administrative decision making. Agency decisions are subject to lobbying by industry groups who can more easily overcome barriers to collective action than consumers [34]. Industry groups have greater lobbying resources compared to public interest groups. Other studies suggest that powerful industry groups manage to manipulate state energy policies [37]. Evidence suggests that environmental groups have been skeptical of participation mechanisms because of the perceived power of pro-development interests to influence the outcomes [18][30].

III. The Model

Given this review of citizen and industry influence administrative decisions, simulating this process requires the

[1] After the US systematized EIAs in the National Environmental Policy Act (NEPA) of 1969, some form of assessment has been required by all US states, and in a growing number of nations around the world (Wathern, 1988, p. 3). The European Union requires EIA for public and private infrastructure projects that are thought to have significant environmental impacts (European Commission, 2012). Most nations in Asia, including China, Korea, Japan, Indonesia and India require some form of EIA before major projects can proceed. EIA's are typically required for these large infrastructure projects involving government funds or lands.

integration of both citizen and industry preferences into modeling efforts. Our agent based model of siting preferences, called SEMPro, simulates bargaining dynamics amongst stakeholders as well as decision makers in the decision process using a spatial bargaining model.

Bargaining models date back to Condorcet's voting paradox [15], and Black [11] and Downs [17] trying to frame a positivist approach to analytical politics. More recently, McKelvey and Ordershook [29] as well as Feldman [19] outline four fundamental assumptions for spatial stakeholder bargaining models: actors are instrumentally rational, with the choice set of feasible political alternatives modeled as a space with complete, ordered and transitive properties. The spatial bargaining approach naturally lends itself to agent-based modeling as stakeholders possess decision agency as well as attributes of preferences over issue spaces, with varying influence and salience [22]. ABM instantiations of spatial bargaining models include Abdollahian and Alsharabati [3] and Abdollahian et al [4].

SEMPro is part of a new class of techno-social [42] and complex adaptive systems' models[1, 2], simulating the interactive effects and feedbacks between human and institutional agency, engineered physical elements, and geophysical systems. SEMPro makes two contributions to our understanding of citizen impacts on agency decisions. First, SEMPro is one of only a handful of multi-agent agent-based models that uses geographical information system (GIS) and detailed census survey data which instantiates real-world dynamics into simulation modeling. Second, SEMPro is the first planning model we are aware of that integrates an ABM with cooperative and non-cooperative game theory models of stakeholder and regulatory decision-making.

SEMPro utilizes the ABM approach as it generates emergent, large-scale system phenomena from the micro-motivations and behavioral interactions of multiple agents. ABM results can then be validated against observed patterns of behavior to analyze what percent of the variation in real-life events that can be explained by the modeling. ABMs are used in techno-social modeling for three primary reasons.

First, agents can be assigned attributes based on stochastic distributions to represent noise or errors in human communication in the model that is reflective of the dynamic, adaptive and strategic nature of human behavior, especially in real-world political and social processes [5]. Introducing stochasticity in agent relationships can dramatically affect networks structures that in turn drive different behaviors [35].

Second, unlike most top-down economic models, agents in ABMs can be assigned heterogeneity in preferences, attributes, or goal-orientation objectives. Brown and Robinson [12] have shown how variations in preferences predict divergent land use outcomes. Finally, the interaction of these heterogeneous agents can lead to non-monotonic outcomes stemming from social mimicry, cooperation and competition in human systems [27]. Thus, ABMs can represent, anticipate and shape the complexity of socio-technical systems better than equation-based models and are more transparent [7].

SEMPro was developed using a system's perspective and parameterizes the project and policy levers that enable scenario analyses required of an effective decision support system [26]. Decision support systems (DSSs) like SEMPro allow users to simulate trade-offs and alternatives to improve energy planning outcomes [35]. DSSs are intended to improve the quality of decision making and need to be generalizable to a wide range of cases [24]. SEMPro can be applied to a wide range of infrastructure siting technologies such as oil pipelines, highways, high speed rail, electricity generation stations, and the subject of this article, electricity transmission lines. In addition to varying project level variables such as engineering attributes in SEMPro, we can also estimate the impacts of changes in risk communication strategies by project stakeholders.

We fuse geophysical and social elements to understand the interactive effects and feedbacks between individual human agency, engineered physical elements and the geophysical environment. Our model is implemented in NetLogo [45], with three different sequential modules, a citizen/CBO formation module, a stakeholder lobbying module and a regulatory decision making module. The citizen agents, stakeholders, and regulators in the model are all trying to maximize their own utilities, given the assumption of bounded rationality. Figure 1 depicts the high level process and multi-module architecture. It runs for up to 25 time steps, with each time step representing 1–2 months of calendar time consistent with regulatory decision time frames in some instances.

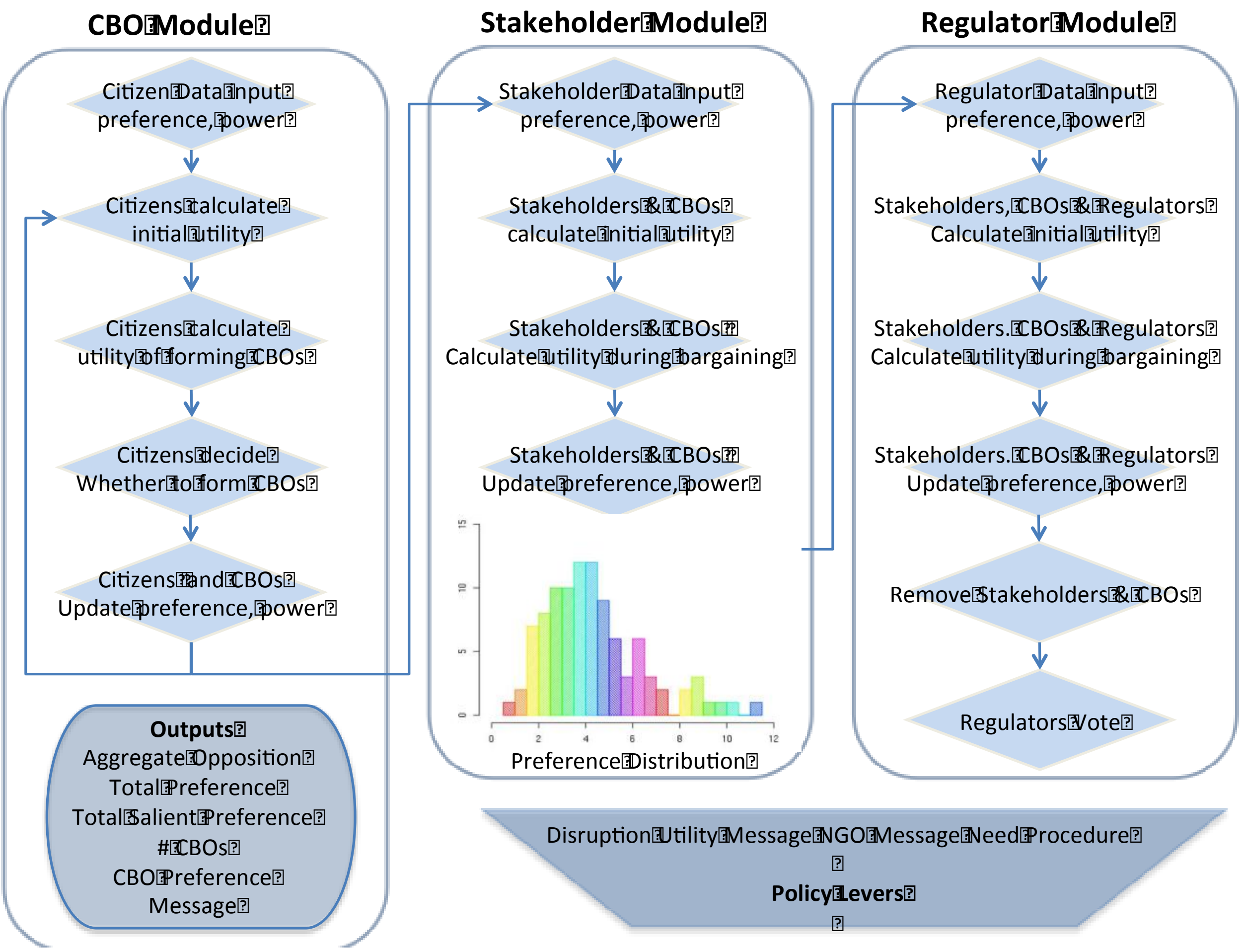

Fig. 1. Three model modules [2]

In the first module, citizens react to energy infrastructure siting projects by forming opinions, interacting with each other, and forming Community Based Organizations (CBOs) that either support or oppose such projects. To simulate this process, citizen agents are queued and processed according to their patch or grid location. GIS-based data on the project size and route, on land use, and on the location of residents informs agent-based simulations of individual interactions. US Census block-group population density data is used to locate citizen agents in the model. Data on education and income by block-group are instantiated as attributes of the agents in the model and provide initial heterogeneity for simulated citizen behavior. Higher values are associated with greater levels of influence in affecting project outcomes and imbue citizens with "power." Wealthier and more educated individuals tend to have a stronger sense of self-efficacy and more resources available for advocacy [33].

In this module, the following is based on calculation of Bilateral Shapley Values (BSVs) of all citizen agents. BSV is a concept in cooperative game theory for explaining coalition formation, and thus a natural modeling strategy to use in CBO formation [25]. Each citizen agent is assumed to be autonomous, with bounded rationality, maximizing it's own utility subject to the geophysical, engineering and social constraints of its environment [46]. BSV computes all combination of all possible coalitions that citizens can join that maximize citizen utility, and then compares all possible coalition utilities in deciding whether or not to join or form a larger CBO. BSV dynamics thus focus on the permutations of individuals in different coalitions based on the marginal utility gained from CBO formation. Expected utility has been described as the "major paradigm in decision making" [38], and our CBO formation is based on cooperative game theory [40].

We also incorporates Social Judgment Theory in each citizen agent's objective function. This theory describes how the positions of two agents can be conceived along a Downsian continuum where the distance between their positions affects the likelihood of one accepting the other's position. A message that is far from a receiver's position is likely to be rejected [39]. For decades, social psychology research has documented that not only do people resist changing their own positions in relationship to new information, but that they might also adopt even more extreme beliefs than before. Social judgment theory finds support in the literature on risk perceptions and social trust. Citizens are unlikely to change their preferences about the project if they distrust the source of risk communications

[23]. In spatial bargaining, trust can be operationalized as the distance between two stakeholder's positions and again is operationalized in the SEMPro model structure.

In the second module of stakeholder bargaining, against this backdrop of political and social opinion formation and risk communication processes, organized stakeholders seek to lobby not only citizen opinions but also other stakeholders to maximize their specific, organizational interests. Berlo's Communications Penetration Model describes how these messages may not be received or accepted because the receiver is not exposed to the message, does not pay attention to the message or does not accept the sentiment of the message [10]. The stakeholder bargaining module takes the emergent CBO formation into consideration in determining stakeholder bargaining outcomes using non-cooperative game theory. Stakeholders will form coalitions if it increases their power to potentially influence the regulatory process as long as the coalition's position is acceptable given the stakeholder's initial position [32].

In the third module, regulators join the bargaining process in the end of the stakeholder module, taking into account CBO formation and public opinion, then bargain among themselves in the regulator module to vote either in support or opposition to the project. Each module updates at each time step. This parallel, linked module processing sequence then iterates. In two continuous time steps, if no new coalition is formed, or no CBOs, stakeholders and regulators change their preference, then the model reaches its steady state equilibrium and will stop.

Actionable policy levers for shaping the transmission siting process include the disruption engineering of the project, utility and NGO messaging outreach, as well as perceived project need and procedure surrounding the process. SEMPro users can simulate changes in the engineering, social, and political attributes of each project as explained in Abdollahian, et al [2]. Each policy lever parameter is normalized along Downsian issue continuum on a 1-10 scale to calibrate the model's internal validity.

The variable that describes the engineering attributes of the project in the model is the level of *disruption* that the project imposes on the community. Disruption is defined as impacts to public health and safety, viewshed impairment, impacts to property values, or other externalities from the infrastructure project (0-1 scale).

Utility-Message is a stakeholder variable that represents the number of pro-development messages the project sponsor sends to citizens to shape public attitudes in each time step.

NGO-Message is the final project level variable that represents the number of anti-development outreach risk communications that non-governmental organizations (NGO) such as the Sierra Club sends to citizens. Our approach propagates utility and NGO messages according to the parameter settings for each simulation in each time step.

Two institutional level variables are included in the model: *Perceived Need* is perceived to be needed by the community. Need can be coded higher when project has been approved by the state regulator and is perceived to provide local system reliability or economic benefits. *Procedure* is an indicator of procedural justice, or to what extent the citizens think their preferences will be included in regulatory decision-making. Experimentalist research confirms that people want to be treated equitably and "other-regarding" equity considerations are a primary driver of citizen behavior.

The primary community level variable is *Talk-Span*, defined as is the distance across which citizen agents talk to each other and make decisions on whether to form CBOs. This can be conceived as the social connectivity of citizens (Putnam, 2001).

IV. VERIFICATION AND SIMULATION

Unit tests were employed in the development of the three modules to verify code functionality. Next, the model outputs were validated against what it claims to be representing. The general goal of validating ABMs is to assess whether the micro-level behavior of the agents generate the expected macro-level patterns [21]. Following Taber and Timpone [41] we employed a two-step validation process. The first was a process validation assessment that tests the model's mechanisms against real-world processes. Our process validity assurance began with selection of appropriate micro-level theories about attitude and behavior diffusion, including social judgment theory [39] and spatially structured (rather than random) interactions [30]. Subsequently, the model's assumptions underlying the model's algorithms were validated against survey data of citizens for a Southern California Edison siting project of Tehachape and Chino Hills. The analysis of the survey data indicated that citizen preferences are moderated by their proximity to the project, their communication networks, and the disruption posed by the project. The effect of trust in the project sponsor on citizen preferences is moderated by distance [33]. Abdollahian et al [2] report other validation tests performed on the model outputs and how the survey data support the model.

After validation and verification, we conducted a quasi-global sensitivity analysis by varying all input parameters across their entire range in three steps (min, mean, max) resulting in 729 runs with up to 25 time steps each, for a total of 14,576 observations. We then pool all the simulations together for a pooled time series regression design estimated with ordinary least squares (OLS) regression with standardized β coefficients for input parameter comparability and model performance.

V. Results

5.1. Citizen Preference

Table 1 contains the results of the OLS modeling of the simulation results. Model 1 in Table 1 is our baseline model for detailing the impact of input parameters on number of citizen messages sent to regulators regarding the siting project. The dependent variable is the interaction term of total messages and median preferences of citizens, which captures not only the number of messages but also the direction of messages—opposition or support for the project.

TABLE 1, Pooled OLS Estimations of Citizen Messages and CBO Preferences

	(1)	(2)	(3)	(4)
	message	**message**	**cbopref**	**cbopref**
disruption	0.109***	0.109***	0.003	0.003
	(0.000)	(0.000)	(0.244)	(0.244)
talkspan	-0.018***	-0.018***	0.909***	0.909***
	(0.000)	(0.000)	(0.000)	(0.000)
ngomessage	0.019***	0.019***	0.010***	0.010***
	(0.000)	(0.000)	(0.000)	(0.000)
utilitymessage	0.016***	-0.005	-0.002	0.051***
	(0.000)	(0.624)	(0.479)	(0.000)
need	-0.014***	-0.014***	-0.013***	-0.013***
	(0.000)	(0.000)	(0.000)	(0.000)
procedure	0.022***	0.022***	-0.004	-0.004
	(0.000)	(0.000)	(0.186)	(0.189)
step	0.959***	0.959***	0.245***	0.245***
	(0.000)	(0.000)	(0.000)	(0.000)
utilitymessage2		0.022*		-0.055***
		(0.025)		(0.000)
N	14556	14556	14556	14556
adj. R-sq	0.933	0.933	0.886	0.886

Standardized beta coefficients; p-values in parentheses

* $p<0.05$ ** $p<0.01$ *** $p<0.001$

First, let us examine the effect of project attributes on citizen opposition. In our simulations, the disruption posed by the project has a very large impact on citizen messages (β = .109) as expected. A one standard deviation decrease in disruption results in a decrease of .109 standard deviations in negative citizen messages. Modifying the project engineering design to reduce disruption by 35%, for instance by increasing the width of the right-of-way, is predicted to result in 11% less citizen opposition.

Project need in model 1 is negative and significant (β = -.014), but is much less important than disruption in explaining outcomes. The results are consistent with observation that citizens express less opposition when the project siting brings significant benefits and is needed by the community. Similarly, perceptions of the procedural justice of the project are negative but not significantly different from zero, suggesting that in these simulations, increasing citizens' perceptions of the procedural fairness of the EIA process is not likely to have an impact on citizen opposition. As expected from the model design, time (β = .959) is positive and significant as the number of messages grows over time. Community attributes also have a large impact on citizen advocacy and activism. Talkspan has a negative impact (β = -.018) on citizen comments, suggesting that citizens express their opinion less frequently in well-connected communities, as they can express the opinion through CBOs.

Turning to the effects of risk communications strategies by project proponents and opponents, NGO message is significant since credible NGO messaging can enhance citizen activism. However the impact of NGO messages is only modest (β = .019) showing effects on activism of about the same magnitude as perceived project need. Although utility risk communications reduce the number of negative messages sent to regulators, the average effect of this variable is not significant. The implications of this finding are discussed in more detail below.

In models 3 and 4, we look at the impact of input parameters on CBO preferences, a key emergent behavior from the first module. CBO preference is the weighted average of the number of CBOs times their preferences categorized by deciles in model output. A higher value for CBO preferences indicates more CBO opposition to the project. The R^2 of 88% in the models shows CBO preference variation explained.

We can see that talkspan is not only highly significant but has the largest impact (β = .909) on CBO preferences. As citizens are able to communicate and exchange opinions across greater distances with more neighbors, the number of citizens joining CBO increases, consistent with existing literature [1, 2]. The time step variable also shows a large and significant impact on CBO formation (β = .245), indicating CBOs opposition increases as time passes. The magnitude of this variable is significantly smaller than for citizen messages (model 1), indicating that CBO preferences are less time dependent than citizen messages.

Utility message and other policy levers like disruption, procedural justice and NGO message do not have significant impact on CBO preferences in the citizen module. Need is significant and positive, counter intuitively indicating greater project need increases CBO opposition. Further investigation of this finding is warranted to discover how project need is channeled through citizen preferences that might have a positive impact on CBO preferences.

5.2. Stakeholder Preference

Next, we turn to an analysis of stakeholder preferences in Table 2. We employ a two stage least square (2SLS) / Instrumental Variable (IV) regression technique for the model outputs for time steps 1-20. The error term from stakeholder preferences are likely to be correlated with

CBO preferences in any given time step. 2SLS is an appropriate econometric technique that uses the predicted value of CBO preferences created in the first stage to predict stakeholder preferences in the second stage regression. This controls for the simultaneous impact of CBOs on stakeholder preferences.

The first stage in model 5 results in an R^2 of .89, indicating 89% of the variation in CBO preferences is explained. Stage 1 in model 5 is very similar to model 3, but also includes negative messages. The inclusion of negative citizen messages truncates the coefficients for both time step and talkspan and makes the need coefficient negative. This is also consistent with model 1 and our theoretical priors. The second stage regression in model 5 indicates the number of citizen messages has a much smaller impact on stakeholder preferences than CBO preferences. This is consistent with observed behavior that citizens need a seat at the table to be heard. Organizational representation is critical to influence stakeholder bargaining in the model.

TABLE 2, 2SLS/IV ESTIMATIONS OF STAKEHOLDER PREFERENCES

First-stage regressions

Number of obs	14556
F (8, 14547)	15782.9
Prob > F	0.0000
Adj R-squared	0.8891
Root MSE	3.3779

cbopref	Coef.	Robust SE	t	P > |t|	{95% Conf. Intvl}	
message	0.8568	0.0051	16.68	0.000	0.0756	0.0957
disruption	-0.0539	0.0085	-6.34	0.000	-0.0705	-0.0372
talkspan	2.5138	0.0080	313.30	0.000	2.4981	2.5295
ngomessage	0.0167	0.0077	2.19	0.029	0.0017	0.0317
utilitymessage	-0.0149	0.0076	-1.95	0.051	-0.0299	0.0000
need	-0.0279	0.0075	-3.70	0.000	-0.0426	-0.0131
procedure	-0.0229	0.0075	-3.05	0.002	-0.0377	-0.0082
step	0.0781	0.0207	3.77	0.000	0.0375	0.1187
_cons	33.9493	0.1745	194.56	0.000	33.6072	34.2913

Instrumental variables (2SLS) regression

Number of obs	14556
Wals chi2(2)	4.0e+05
Prob > chi2	0.0000
R-squared	0.9728
Root MSE	1.217

stakeholderpref	Coef.	Robust SE	t	P > |t|	{95% Conf. Intvl}	
cbopref	0.7232	0.0012	601.33	0.000	0.7209	0.7256
message	0.0155	0.0004	37.80	0.000	0.0147	0.0163
_cons	10.3756	0.0582	178.35	0.000	10.2616	10.4897

Instrumented: cbopref
Instruments: message disruption talkspan ngomessage utilitymessage need procedure step

5.3. REGULATOR PREFERENCE

Table 3 shows the variables that impact regulator preferences using the same instrumental variable approach where we first predict stakeholder preferences and then use that value to predict regulator preferences. The R^2 indicates that 30% of the variation in regulator preferences is explained by the stakeholder preferences and citizen messages. We expect the R^2 for regulator preferences to be lower than that of the stakeholder equation as regulators have to balance additional considerations, such as competing policy goals and political issues, in their decisions. In addition, the R^2 is lower as regulators only interact with CBOs and other stakeholder from time step 16 to 20, and then decide amongst themselves from time step 21-25.

The table shows that negative citizen messages have a larger impact on regulator preferences than stakeholder preferences in the previous table. A one standard deviation increase in citizen messages results in a .621 standard deviation (β=.621) increase in regulator oppositional preferences.

This differential impact of citizen activism on stakeholder and regulator modules is critical. The impact of citizen messages on regulator preferences is over two times larger than their impact on stakeholder preferences. Citizen preferences impact stakeholder preferences through the efficacy of CBOs who bargain with other stakeholders. On the other hand, the modeling predicts that elected or appointed regulators are more balanced in their response to citizens and stakeholders' demands.

TABLE 3, 2SLS/IV ESTIMATIONS OF REGULATOR PREFERENCES

First-stage regressions

Number of obs	2908
F (3, 2904)	53966.0
Prob > F	0.0000
Adj R-squared	0.9786
Root MSE	1.1716

stakeholderpref	Coef.	Robust SE	t	P > |t|	{95% Conf. Intvl}	
message	-0.8558	0.0195	-4.39	0.000	-0.1238	-0.0474
message^2	0.0004	0.0008	4.47	0.000	0.0002	0.0005
cbopref	0.6878	0.0017	397.10	0.000	0.6844	0.6912
_cons	18.2925	1.1325	16.15	0.000	16.0719	20.5131

Instrumental variables (2SLS) regression

Number of obs	2908
Wals chi2(2)	1504.29
Prob > chi2	0.0000
R-squared	0.2960
Root MSE	5.4094

regulatorpref	Coef.	Robust SE	t	P > |t|	{95% Conf. Intvl}	
stakeholderpref	0.4213	0.0112	37.77	0.000	0.3994	0.4431
message	0.6208	0.2200	2.82	0.005	0.1897	1.0519
message^2	-0.0022	0.0010	-2.11	0.035	-0.0043	-0.0002
_cons	-34.622	11.5271	-3.00	0.003	-57.214	-12.029

Instrumented: stakeholderpref
Instruments: message message^2 cbopref

V. DISCUSSION

The results from the model simulations show important insights for planning processes as the linkages between emergent citizen behavior and stakeholder and regulator preferences are complex. First, citizen advocacy in institutional processes will be greater when threats to their communities are greater as evidenced by the positive impact of the disruption variable, which is consistent with the risk communication research.

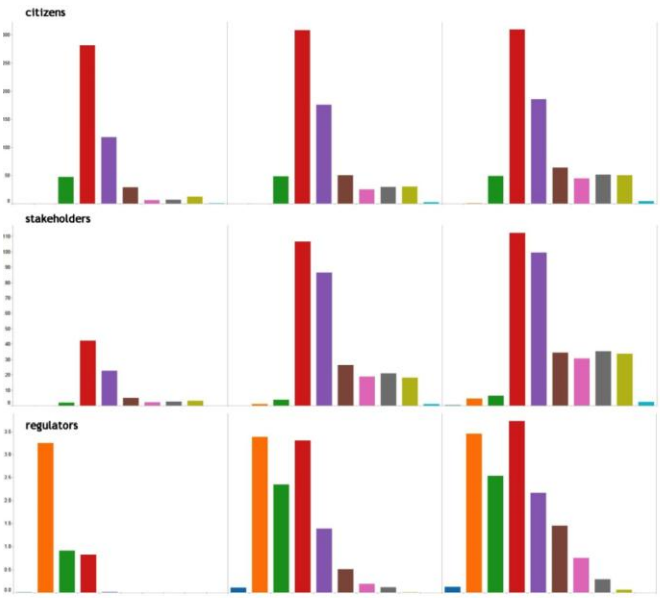

Figure 2 Agent Histogram Density for time step=1, 10 and 20

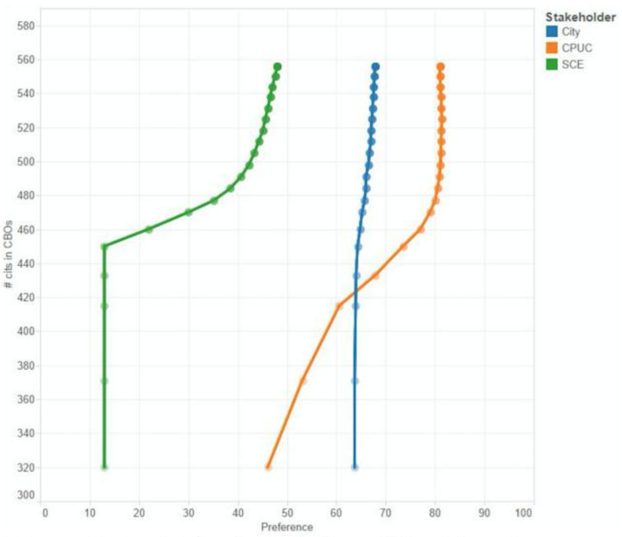

Figure 3 Citizen CBO Size and Preference

Second, emergent citizen behavior can dramatically alter institutional outcomes over time. Figure 2 shows histograms of average citizen, stakeholder and regulator preferences in the first, middle and last time steps in all of the simulations. What is notable across all three categories is the shift towards greater project opposition over time across all three levels of analysis.

The third finding is communities with more well-connected citizens represented in the model by larger talkspan are more likely to be effective blocking or altering infrastructure projects. Talkspan implies citizens talking across a greater geographical distance in the model and predicts fewer CBOs as well as more citizen opposition messages. Talkspan can be conceived of as the level of betweenness in social network terms, with larger nodes being more socially connected to other individual citizens. For details, see Abdollahian et al. [2] analysis on betweenness and eigenvector centrality of the model's social network outputs.

Figure 3 above shows several simulations of citizen CBO representation and their resulting preferences for three groups, the city, one of the regulators the CPUC and the utility Southern California Edison (SCE). Here we can see the varying response elasticities of all three groups to increasing CBO size. While the city seems to be relatively inelastic to CBO sizes, both the regulator and the utility show marked change. The CPUC regulator here starts at an indifferent preference (approximately 50) but slowly moves towards project opposition (at 80) in a linear fashion as CBO participants move from 300 to around 450. Afterwards, there seems to be marginal returns for increasing opposition with more CBO participants. What is most interesting is the utility's staunch support for the project (at a preference of 10) in the face of increasing opposition, until a tipping point is reached where sharp, major concessions (shifting towards indifference at 50) are granted in order to maintain project viability. This seems to be consistent with many public agencies' past modus operandi of 'decide then defend' for works projects.

The results show several key emergent behaviors from infrastructure siting including citizen interaction and CBO formation. Our simulations explain why CBOs are effective in aggregating citizen preferences and altering stakeholder preferences. The finding that citizen messages are relatively more important to regulators than stakeholders is consistent with the institutionalized comment process. Our findings indicate that citizen comments are surprisingly influential in determining regulators' preferences, indicating a level of political responsiveness to social sustainability issues that supports the efficacy of institutionalized planning processes. At the same time, we also find that CBOs positions are important in determining stakeholder preferences.

We posit two important methodological advances from our current modeling approach. First, the SEMPro design that links an ABM with GIS data is critical for valid inferences about citizen participation as citizen interactions emerge from local conditions and attributes; all politics are local. Second, linking ABM with spatial bargaining models permits the analysis of the interactions and linkages between citizen emergent behavior and institutionalized decision-making modalities. By linking citizen behavior with stakeholder and regulator preferences, SEMpro explicitly simulates the impact of micro-level behavior on macro-level institutional outcomes, a fundamental challenge in social policy spaces.

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A stability analysis of the Nord Pool system using hourly spot price data

对采用按时现货价格数据的北欧电力库系统之稳定性分析

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Abstract - **Electricity prices are known to spike during peak hours, only to revert to normal levels during off-peak hours. We introduce a generalization of the time-varying independent spike model commonly used to model the electricity spot price from daily data to hourly data to cope with this feature.**

We let the probability of extreme prices depend on several variables, such as consumption, reserve margin or wind power. The model can then be used to forecast the risk of extreme prices.

More factors become relevant for predicting extreme events when moving to hourly data, but consumption is still the most important factor. The methodology is showcased by illustrating how extreme prices can be forecasted by predicting the consumption.

Keywords - **Electricity Market, HMM, Forward contract, EM-algorithm, Stability analysis.**

I. INTRODUCTION

Power generation has historically been operated according to some centralized designing. A vertical market structure was common, as that ensured that production plans would cover expected consumption and some extra margin, see [1]. Deregulation of the electricity market began in Chile in the early 1980s, whereupon many countries followed. A reasonably fair market means that prices will contain information about the current state of the market, cf. [2], and also information about the underlying power system, see [3]. One example of the quality of the information carried in markets is presented in [4] where they show that predictions markets generally outperformed election polls in nearly every U.S. Presidential elections between 1988 and 2004.

The electricity spot price is characterized by several features that are not common in other commodity prices. These include yearly, weekly and intra-day seasonality as well as extreme (very high and very low) prices. The latter are referred to as spikes and drops, see [5], and carry important information about the state of the physical power system, cf. [3, 6]. The price information was used to assess the stability in the Nord Pool power system using daily data under four different scenarios in [7]. They found that the consumption influenced both the probability of having spikes and drops, as well as the probability of reverting back to the normal conditions. It was expected that other variables, such as the reserve margin or wind power, also would influence those probabilities, cf. [8], but they found no statistical support for that hypothesis.

It can be speculated that variations in the wind power or reserve margin is operating on a shorter time scale than days, and that wind power therefore was deemed unnecessary in [7]. The purpose of this paper is to study the stability of the Nord Pool power system by using market data as proxy. It extends currently used models to cope with hourly data, in order to better understand the within day stability, and to explore if factors like wind power production and the reserve margin are relevant on a shorter time interval.

The remained of the paper is organized as follows. Section II discusses the electricity market and introduces a suitable statistical model. Estimation of the parameters is discussed in Section III while Section IV demonstrates how the methodology can forecast spikes. Section V concludes the paper.

II. A MODEL OF THE ELECTRICITY SPOT

The integration of renewable energy into the power system has made production planning much more complex, as we cannot know for sure what the production will be, cf. [9]. This complexity has resulted in volatility clustering and extreme prices in the electricity spot price, see [10] for an overview of stylized facts in the electricity spot price.

It is well known that the demand for electricity is inelastic, meaning that customers are rarely adopting their consumption according to the price, even though [11] and [12] presents strategies for changing this. The demand is varying on a yearly, weekly and daily scale, introducing seasonality in the price.

The yearly seasonality can be difficult to model, as it is due to physical processes that follow a cyclical pattern, but where the timing varies between years. That makes models that uses sums of trigonometric functions or wavelets, see [13], prone to overfitting the data. However, these techniques are still useful for modeling the weekly and daily seasonal patterns, as those patterns are constant over time and trigonometric methods do also work well when removing the seasonal component for a fixed set of data. It was noted in [14] that the spot and future prices are cointegrated, as their price implicitly depends on the same factors, a feature that we will use in this paper.

The extreme prices often cluster, as there could be several consecutive days with extreme prices before reverting to normal conditions. It was argued in [15] that this is best described by a Markov Regime Switching (MRS) model.

The electricity price is also known to be mean reverting, see [10], meaning that the price fluctuates around some equilibrium price, and will return to it even if some external disturbance caused causes a temporary deviation.

Our model belongs to the class of second generation Independent Spike Models, which is a special case of the Markov Regime Switching model, see [5, 16]. Early models used two regimes, but it is nowadays common to have three regimes, see [17]. These are the regime for high prices called spikes (S), the regime for low prices called drops (D) and a base regime (B) for normal prices. The transition between these is often assumed to be governed by a time invariant transition probability matrix, but recent studies indicate that this may be suboptimal, cf. [8, 7].

Allowing the transition probabilities to be time varying makes it possible to model the increasing probability for spikes when there is a shortage of electricity, and correspondingly to model the increasing probability for drops (and decreasing probability for spikes) when there is excess supply. The excess supply has even resulted in negative prices in both the German and Danish markets. Instead we parametrize the transition matrix according to

$$P(x_t) = \begin{bmatrix} p_{BB}(x_t) & p_{BS}(x_t) & p_{BD}(x_t) \\ p_{SB}(x_t) & p_{SS}(x_t) & 0 \\ p_{DB}(x_t) & 0 & p_{DD}(x_t) \end{bmatrix} \quad (1)$$

where the models has been restricted so that transitions directly from spikes (S) to drops (B) or vice versa are prohibited and $p_{BB}(x_t) = 1 - p_{BS}(x_t) - p_{BD}(x_t)$. Each probability (here we take $p_{BS}(x_t)$ as an example) is a function of an explanatory variable, given by

$$p_{BS}(x_t) = \frac{\exp(\beta_{BS,0} + \beta_{BS,1} x_t)}{1 + \exp(\beta_{BS,0} + \beta_{BS,1} x_t) + \exp(\beta_{BD,0} + \beta_{BD,1} x_t)}$$

This multinomial logistic mapping is common in regression problems, see [18] for details. The denominator ensures that all probabilities will be between zero and one while the numerator is made up of a base level $\beta_{BS,0}$ and a term that captures the influence of the explanatory variable $\beta_{BS,1}$. The change in probability when changing x_t is closely related to $\beta_{BS,1}$. We also tried quadratic forms and/or combinations of factors but found no convincing statistical support for any of these, see [19]. All explanatory variables was normalized according to

$$x_t = \frac{x_t}{\max_{u \in 1:T} x_u} \quad (2)$$

This does not change the model but it makes it easier to interpret and compare the estimates between different explanatory variables. Not scaling the variables would result in different estimates if the consumption was measured in MWh or GWh. The influence after scaling the variables varies between $\beta_{BS,0}$ when x_t is close to the smallest value and $\beta_{BS,0} + \beta_{BS,1}$ when x_t is at the largest value.

What remains is to specify the models for each regime. Most second generation Independent Spike Models use some forward contract as the yearly seasonal adjustment. It was noted in [14] that the spot price and forward price is cointegrated, meaning that the difference between them is a stationary process. It can be shown that the forward price F_n at time t_n is given by the discounted, risk-neutral conditional expectation of the average spot price

$$F_n = p(t_n, t_n + T) E^Q \left[\frac{1}{T} \int s(u) du \right] \quad (3)$$

where $s(\cdot)$ is the electricity spot price and $p(t_n, t_n + T)$ is a zero coupon bond with maturity T discounting the value back to time t_n. The spot price and the difference between the logarithm of the spot price $y_n = \log(s_n)$ and the logarithm of the one month ahead forward price $f_n = \log(F_n)$ are presented in Fig. 1, confirming the strong relation between the spot and forward. Daily and hourly effects were coped with by using dummy variables, cf. [20].

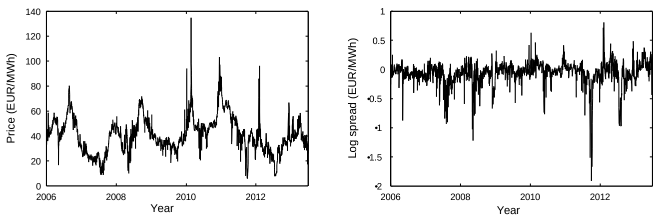

Fig 1. The spot price (left) and spread between the logarithm of the spot price and the logarithm of the one-month ahead forward price on Nord Pool (right) between 2006 and 2014.

The dynamics for the regimes are given by

$$y_{n+1} = \begin{cases} y_n + a(\mu_n - y_n) + \sigma y_n^{\gamma} z_n & if\ R_{n+1} = B \\ f_n + \xi^S & if\ R_{n+1} = S \\ f_n - \xi^D & if\ R_{n+1} = D \end{cases} \quad (4)$$

where R_n is a hidden Markov chain governing the state of the market. Similar models are used to describe the economy with booms and recessions. The mean reversion level $\mu_n = \eta f_n$ in the base regime is a factor compensating for the risk premium η times the logarithm of the month ahead forward, a and σ are positive constants while ξ^S and ξ^D are independent and identically distributed (*iid*) random variables having some known distribution (typically log-normal or Gamma), see [17] for various European markets. We take the risk premium as constant, even though [21] indicates that it may be related to the levels in the water reservoirs (a substantial part of the power traded at Nord Pool is generated in hydro power plants). However, we believe that this approximation is justified as the effect from misspecifying the mean is small compared to misspecifying the variance when it comes to the regime classification which is the primary purpose of the model.

III. Empirical Study

We have fitted several models to daily and hourly data, see [19] for details. The EM algorithm was used to optimize the log-likelihood function, cf. [17, 22]. The EM algorithm is often more robust than direct maximization of the likelihood function, see [18].

A general result that is valid across several markets and spike distributions was that there was no need for the CEV dynamics when introducing the time varying transition probabilities, γ=0. This is in line with the findings in [5].

The parameter estimates when using daily observations from Nord Pool between 2006 Q1 (or 2009 Q1) and the end of 2013 are presented in Table 1. The consumption and production are highly relevant variables, as noted in [7]. The reserve margin does on the other hand not significantly influence the probability of going from any state to any other state (the β_0 parameter provides an intercept, while the β_1 parameter gives the actual influence of the external variable), while wind power production helps a little, as more wind power increases the likelihood for reverting to the base regime when in the spike regime ($\beta_{SB,1} > 0$).

TABLE 1, Estimated parameters for the three state MRS model using Vasicek dynamics together with Gamma spikes for daily price in the Nord Pool System. Significant parameters are emphasized in bold. All time series are evaluated from 2006 Q1 until June 30th in 2013, except for the wind power that is estimated from 2009 Q1 to 2013.

Variable	$\beta_{BS,1}$	$\beta_{BD,1}$	$\beta_{SB,1}$	$\beta_{DB,1}$
Consumption	**28.14**	**-17.54**	**-16.34**	**7.71**
Production	**31.23**	**-16.75**	**-33.61**	4.42
Reserve Margin	1.11	0.08	0.45	-1.48
Wind power	1.66	1.20	**5.37**	-4.43
Variable	$\beta_{BS,0}$	$\beta_{BD,0}$	$\beta_{SB,0}$	$\beta_{DB,0}$
Consumption	**-27.84**	**6.53**	**13.27**	**-6.02**
Production	**-30.96**	**-5.87**	**29.80**	**-4.31**
Reserve Margin	**-4.45**	**-4.30**	**-1.79**	**-1.63**
Wind power	**-4.58**	**-4.52**	**-3.96**	**-0.48**

Moving on to hourly data presents a slightly different story, see Table 2, where we see all parameters that were significant when using daily observations still are significant using hourly observations. However, we also see that the reserve margin is an important variable, with all parameters being significant. Wind power is also important, with all relevant variables being significant, but we also note that the $\beta_{BS,1}$ parameter changed sign. Please note that the parameters are slightly different as the normalization of the external variable changed slightly, cf. Eq. (2).

TABLE 2, ESTIMATED PARAMETERS IN THE TRANSITION MATRIX FOR THE THREE-STATE MRS MODELS USING VASICEK DYNAMICS AND GAMMA SPIKES FOR HOURLY OBSERVED PRICES IN THE NORD POOL SYSTEM. SIGNIFICANT COEFFICIENTS ARE EMPHASIZED IN BOLD. ALL TIME SERIES ARE EVALUATED FROM 2006 Q1 UNTIL JUNE 30TH IN 2013, EXCEPT FOR THE WIND POWER THAT IS ESTIMATED FROM 2009 Q1 TO 2013.

Variable	$\beta_{BS,1}$	$\beta_{BD,1}$	$\beta_{SB,1}$	$\beta_{DB,1}$
Consumption	**34.12**	**-10.81**	**-3.64**	**2.87**
Production	**31.72**	**-12.14**	**-6.35**	**3.86**
Reserve Margin	**-4.17**	**0.81**	**0.81**	**-2.40**
Wind power	**-0.95**	**3.83**	**-9.78**	**-0.68**
Variable	$\beta_{BS,0}$	$\beta_{BD,0}$	$\beta_{SB,0}$	$\beta_{DB,0}$
Consumption	**-32.22**	**2.07**	**2.00**	**-3.62**
Production	**-30.99**	**2.64**	**4.30**	**-3.62**
Reserve Margin	**-12.93**	**-9.42**	**-0.19**	**-1.53**
Wind power	**-11.27**	**-10.40**	**-0.86**	**-2.10**

Models are often compared in terms of AIC or BIC, see [23]. This is equivalent to comparing the log-likelihood of the models in this paper (as all models have the same number of parameters), $log(L) = \sum log\ p(x_n|x_{\{1:n-1\}})$ where the transition probability $p(x_n|x_{\{1:n-1\}})$ is derived from the model. We find that the consumption still is the best explanatory variable by quite a margin, see Table 3. The estimated parameters also have the current signs, in the sense that their effects are what we expected them to be.

The reason why the consumption outperforms the reserve margin is not clear to us, but it could be that the reserve margin can be computed in several ways, as for example transmission capacity may be included in the definition. The numbers we used may therefore not represent the actual, controllable reserve margin well enough, cf. [8].

TABLE 3, LOG-LIKELIHOOD WHEN USING THE CONSUMPTION, PRODUCTION, RESERVE MARGIN AND WIND POWER AS EXPLANATORY VARIABLES, EVALUATED ON DATA FROM 2009-10-01 TO 2013.

Explanatory variable	$\log(L)$
Consumption	52 225
Production	51 381
Reserve margin	49 100
Wind power	49 087

IV. SIMULATION STUDY

We consider two winter weeks during the winter of 2015 that are not part of the data in Section III. First, we study the electricity spot price and consumption for the Nord Pool system between January 10th (which is a Saturday) until January 18th (which is the following Sunday). These data are presented in Fig. 2 (data can be downloaded from Nord Pool, http://www.nordpoolspot.com/historical-market-data/). It can be seen that the price increases somewhat during the working days (12/1-17/1) and peak hours, but also reverts to the normal price levels during off peak hours. The price peaks coincide fairly well with the consumption peaks.

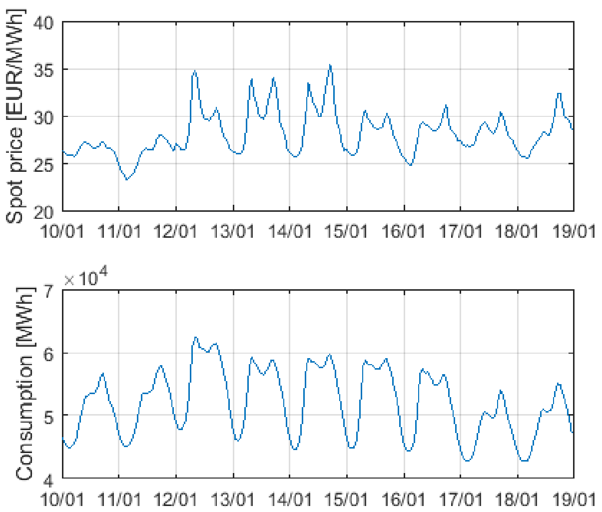

Fig 2. Electricity spot price (top) and consumption (bottom) for the Nord Pool system between January 10th (Saturday) and January 18th (Sunday) 2015.

It is well known that consumption is comparably easy to predict, see e.g. [24, 20] for an overview of methods. We can therefore forecast the consumption in order to assess the risks for spikes in the upcoming week. We have approximated the forecast by the actual consumption in the top panel in Fig. 3. The consumption is then used to forecast the probability for spikes by iterating the latent Markov chain governing the regime from 16/1 and onwards (middle panel). The increase in consumption from Monday to Friday translates into large spike probabilities. We also note that the persistence of the spike regime largely is determined by the consumption. These probabilities can be compared to the actual electricity spot prices during the same period (lower panel). We find that the model is able to predict the spikes, using only the consumption.

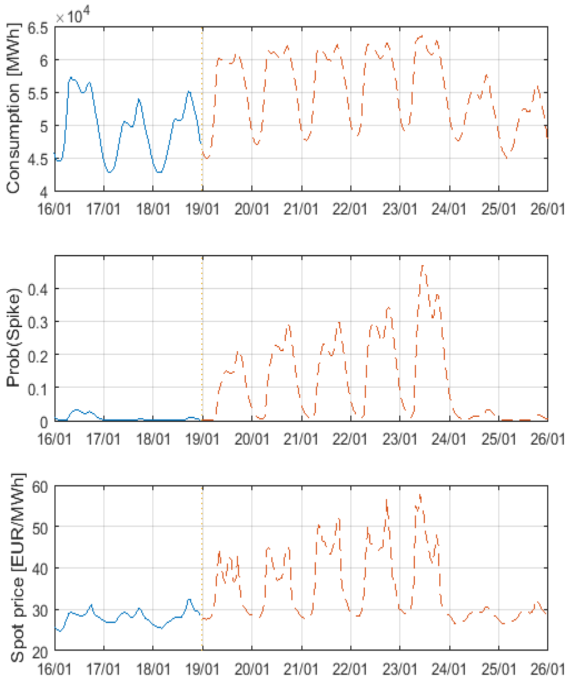

Fig. 3 Known data up until Sunday 18th January (solid line) and ”Predicted” (dashed line) consumption for the upcoming week (top panel), the resulting spike probabilities (middle panel) computed from the consumption and actual electricity spot price (bottom panel) for the second week in January, 2015.

V. Conclusion

This paper presents an extension of the time invariant Independent Spike Model introduced in [7] by considering hourly observations rather than daily observations.

We found that the model can swiftly move from the base regime to the spike regime during peak hours only to revert later during the evening. It is now the external variable (typically consumption) that determines the persistence of the extreme prices. This is in stark contrast to the standard time homogeneous model where the persistent is constant (with exponentially distributed durations).

We also found support for the hypothesis that wind power and the reserve margin influences the probability for spikes and drops, but the likelihood based information criteria clearly ranked the consumption as the most important variable.

The model was used to demonstrate how consumption forecasts can be used to forecast spikes (including reversion to the base regime during off-peak hours). This could a very useful proxy for the stability in the physical power system!

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Regional energy strategy for selected region in Poland as a result of foresight project

作为预见项目结果的波兰选定区域之区域能源战略

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Abstract - **The paper describes the foresight methodology, especially the Delphi survey, which was conducted in 2010 in Lower Silesia. The Delphi survey was based on experts' opinions about technological theses. The research contains the analysis of the influence of particular theses on the implementation of the strategy's main aim. The mission of the strategy is to ensure energy security in the conditions of innovative and ecological regional energy sector, which uses local energy sources and, additionally, is open to competition. We used the foresight methodology for the following things: to identify main barriers as well as positive and negative factors for implementing Delphi theses; and to formulate the regional energy strategy, its mission, aims and activities for regional authorities.**

We propose to compare the Delphi's results to the results of quantitative methods, mainly growth curves, in order to control the results obtained by semi-quantitative methods, based on experts' opinions. The comparison could be made only for separate results because the main barrier is the access to relevant and representative data. There will be presented a short analysis for a separate thesis.

Keywords - **foresight, Delphi methods, growth curves, logistic substitution model, regional strategy**

I. INTRODUCTION

On the background of directions and current problems (e.g. innovativeness in the energy sector and economies; energy security in the European, domestic and regional scope; an ecological trend connected with climate changes) of energy policy in the European Union, the paper will present an approach to create a regional energy strategy for Lower Silesia (Poland). This is a special region because of its location, as it is bordered by Germany and by the Czech Republic. There are similar geographical characteristics (climate conditions and energy sources) near the border with the German region (Saxony), but there is a completely different structure of energy sources (energy mix), because in Germany the share of renewable energy sources (RES) is much higher. The domestic and regional policy influence this situation. Therefore, the paper presents the selected results of foresight research conducted by our team at Wroclaw University of Technology (WUT, Poland), which were obtained during the project *Energy Development Strategy of Lower Silesia by Using Foresight Methods*, co-funded by the European Regional Development Fund (ERDF)[1].

The research was based on Delphi methods and the experts were able to identify the most sophisticated theses according to previously identified energy problems which take place in Lower Silesia. For each thesis they identified, inter alia, the most probable time period required for completion, positive factors for its implementation as well as possible barriers and negative factors. Based on the results of three rounds of the Delphi survey the research team created a proposal of strategy for the researched region and it selected the groups which are:

- the most important for the region,
- supporting energy security in the region,
- supporting innovation in the regional energy sector,
- the most economic for regional society and the most important for ecological aspects.

In the next step of our research key actions for local authorities were defined. We used a mix of quantitate, semi-quantitative and qualitative research methods. Because

[1]Co-funded by Operational Programme Innovative Economy 2007-2013,
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of the specification of our research, which was focused on innovative energy technologies, the use of quantitative methods was limited to a narrow dimension in order to forecast key energy parameters in the consumption and production of: electricity, gas, heat.

Three years after finishing the foresight project the author [5] performed the quantitative research using the logistic substitution model (LSM) for the verification of the results of the semi-qualitative method – Delphi method – for one selected thesis dedicated to the development of renewable energy sources in Lower Silesia.

The main aims of the paper are to present the research method and the key results of the foresight project; and the comparison of the results for semi-quantitative and quantitative methods for the selected thesis. In the last part of this paper we present some comments about the barriers to implementing the whole strategy at regional level.

II. THE ENERGY STRATEGY FOR LOWER SILESIA

2.1. THE ENERGY SECTOR IN POLAND AND LOWER SILESIA – MAIN CHALLENGES

The Polish territory totals to 322.75 thousand km^2. The population was 38,478,602 in 2014 and its density – 123 persons per km^2. Poland is not a rich country, the GDP in 2014 was 1 728,676.6 m PLN (it is circa £309 m) and GDP per capita – 44,919 PLN. Polish GDP per capita in relation to the wealthiest country in the EU (at PPP) in 2013 year equalled 51%, but the growth rate in 2014 was 3.2 %.

In 2013 the key data for the energy sector was as follows:

- total energy production – 3006 PJ
- primary energy consumption – 4 465 PJ
- the share of RES in gross final energy consumption – 11.3%
- electricity generated from RES – 17 066.6 GWh
- energy intensity of the economy – 333.2 kgoe/1000 EUR.

There is much emission of greenhouse gases in Poland, e.g. in the year 2012 the total emission of CO_2 totalled 320,862 thousand tonnes and the emission of CO_2 per capita reached 8.6 t in the year 2011. This is the result of the large portion of fossil fuels (like coal and lignite) used in the production and consumption of primary energy as well as in electricity and heat. For example in 2013 50% of electricity came from coal, 34% from lignite, 3% from gas fuel, 10% from RES and 3% from the other energy sources. The greates part of renewable energy comes from solid biofuels (80.3% of RES) [1]. The energy produced from biomass is made by conventional power stations and CHP plants. These companies either burn conventional fossil fuels and biomass together, or only biomass. Because they produce ‘green energy’ according to current regulation they obtain support in the form of ‘green certificates’. This is a process of displacing the small independent RES by big energy companies. In addition the biomass is transported from remote areas, which is not neutral for the environment. Other RES that have undergone dynamic development in Poland are wind farms. In 2013 more than 35% of renewable energy in electricity production came from wind. This situation draws the need to develop grids. However, the number of new wind turbines planned by potential investors are much bigger than the TSO and DSOs can technically connect to grids.

Other problems in Poland connected with the energy sector are: the depreciation of infrastructure, the number of international electricity grid connections and the lack of gas supply diversification. These facts influence the energy security.

Lower Silesia is a region in south-western Poland. According to the macroeconomic indices the region is one of the best developed in Poland but the German regions (e.g. bordering Saxony) and the Czech regions (Kraj Liberecki and Kraj Kralowohradecki) have better value in macroeconomic indices. The population density in Lower Silesia is larger than the average population density in Poland, and it is similar to one in Kraj Liberecki. The global irradiation and solar electricity potential of Lower Silesia nearly amounts to 1,200 kWh/m^2 and is similar to Czech regions and Saxony in Germany, but the insolation in Leipzig and Dresden is smaller than in Lower Silesia [2]. This data is interesting because the value of installed solar capacity in Saxony is much larger than in Lower Silesia. Moreover, there are the autonomous local areas where 100% or almost 100% of energy comes from RES in Saxony, but in Lower Silesia there are none. There are some reasons for this situation, which are shortly described below:

- financial support addressed to local society in order to install the RES is bigger in Germany,
- development of RES investments, an education process about RES and ecological issues, which started earlier in Germany than in Poland,
- higher average income per capita in Saxony, e.g. the Gross Regional Product (GRP) per capita for Lower Silesia is comparable with its value for Czech regions but it is two times lower than in Saxony,
- a different system of regulation at local and state levels in Germany. In Poland regulations support mainly big energy companies and for this reason they make RES investments.

If we compare the regional growth rate, we can see that Lower Silesia is developing faster than bordering regions in the Czech Republic and Germany, which shows the higher development potential of the Polish region.

Looking at characteristics of the energy sector in Poland, and especially in Lower Silesia, we see that the main challenges are connected with:

- providing energy security,

[2] The values taken to the comparison come from yearly electricity generated by 1kW$_{peak}$ system with performance ratio 0.75 kWh/kW$_{peak}$ [re.jrc.ec.europa.eu/esti/index_en.htm].

- improvement of energy efficiency in whole energy logistic chain, from the energy production to energy consumption (at user level),
- bigger share of the RES in total energy production and consumption.

In these conditions the foresight research has sophisticated function for strategic approach at regional and state levels.

2.2. THE CHARACTERISTIC OF METHODOLOGY TO BUILD THE REGIONAL-ENERGY STRATEGY FOR LOWER SILESIA

The project *Energy Development Strategy of Lower Silesia by Using Foresight Methods* was conducted by an interdisciplinary team from WUT from 2009 to 2011. We realised 5 tasks (T) and used complementary foresight methods, which is in accordance with Popper's approach who recommends not only mixed-method based on quantitative and qualitative methods, but, mainly, the mixed-method based on two dimensions [4]:

- expertise versus interaction,
- creativity versus evidence.

These tasks are:

- T1: The analysis of the present situation of the energy market on Lower Silesia (a survey, a lecture review, an analysis of historical data, expertises, a "good practices" conference)[3],
- T2: The questionnaire study among the experts and its analysis and verification (a few expertises, a survey research using Delphi method, a survey, 4 experts' panels (dedicated to technology, economic, ecological and local self-government aspects as well as social issues)),
- T3: The stochastic analysis of the real data from the energy sector – a forecast (extrapolation of trends, time series forecasting),
- T4: The preparation of the document *The energy development strategy on the Lower Silesia* (scenarios, a SWOT analysis, brainstorming, expertises),
- T5: The preparation of the monitoring system of strategy implementation (benchmarking).

In Delphi research two kinds of experts participated:

- 83 experts from industry (including researchers) who completed Delphi surveys. The experts were divided into 4 topical groups: electro-energy, gas, heating and renewable energy,
- 18 key experts who wrote analyses, some of them supported the research team as advisers.

The central and most important part of our research was task No. 2. The first step was to define the theses. We defined 73 theses which were assigned to one of 15 topical groups. The base of the theses and their assignment, which was input to the first Delphi survey, was finished after the consultations with key experts and after the first technological experts' panel. Finally, in the next step of our research, we took one thesis less, namely 72 theses which were indicated by experts as supporting innovative solutions (including technologies[4]) for our region and divided them into the 15 topical groups: (1) Energy production based on coal and lignite, (2) Energy technologies using biomass, (3) Energy technologies using biogas, (4) Energy systems based on wind, (5) Energy systems based on water, (6) Energy systems based on solar energy, (7) Energy production based on nuclear power engineering, (8) Technologies in natural gas industry, (9) Innovative technologies of energy storage, transmission and distribution, (10) Technologies of heat, heating and cooling systems, (11) Fuel cells, (12) Smart Grids (SG), (13) The behaviour of users and technologies improving the efficiency of energy use, (14) Transport and energy based on hydrogen and synthetic fuels , (15) Organizational and structural changes at regional and local levels. The last group of theses (the 15th one) was added after the 1st experts' panel.

The second stage was Delphi surveys consisting of three rounds. In the first Delphi survey 11 questions was assigned to each thesis. In the first round of survey the experts could also modify the theses. The questions concerned: the period when the thesis will be realised, business which may develop if the thesis will be implemented, the benefits for the region as the results of its implementation, positive and negative factors, and the cost of its realization. The second survey was similar to the first one but it was more detailed, and the number of theses was reduced because the least important theses for the region were not taken into account. The questions concerning on benefits, and barriers were more accurate. However, the third survey was different because it had other goals. It concentrated on three scenarios regarding ecological, business (economic) and social aspects. In the third survey there were only three questions to each scenario. The experts marked the relevance of each thesis for a researched scenario in the first question. In the second one they chose the period when every thesis would need to be realized for each researched scenario. In the last question they marked activities (like: financial, educational, related to the regional law and other) which could be introduced if the scenario were to be realised. In this way some important information was obtained to construct energy strategy based on the scenarios.

The experts fulfil two functions in the foresight research. They are sources of tacit knowledge and they are the group representing the society (local authorities, regulators, energy companies, scientists, business connected with energy services and equipment). The experts participate indirectly in the construction of the scenarios and the energy strategy addressed to Lower Silesia.

The proposal of the regional-energy strategy was the main result of our foresight project. The approach to build the strategy − including its mission, main aims and actions dedicated to different kinds of participants − is presented in

[3] There is the list of methods used in the brackets.

[4] The experts assigned the technologies to one of 4 phases of technology life cycle. We selected only technologies belongs, according to experts opinions, to the first, second or third phases which means the most innovative technologies for the region.

Fig. 1. Fig. 2 shows the mission as well as main and detailed goals of this strategy.

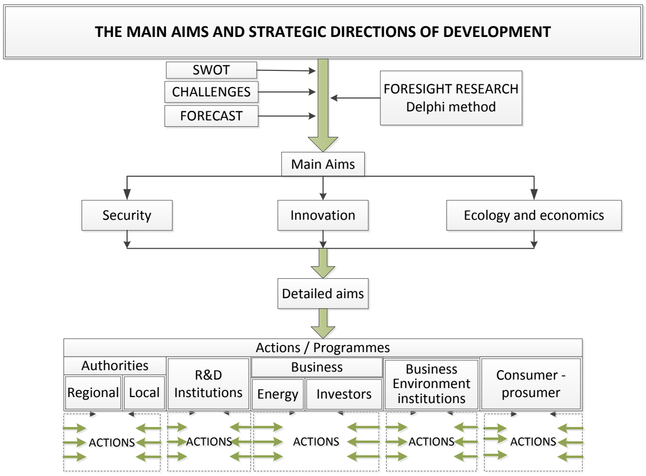
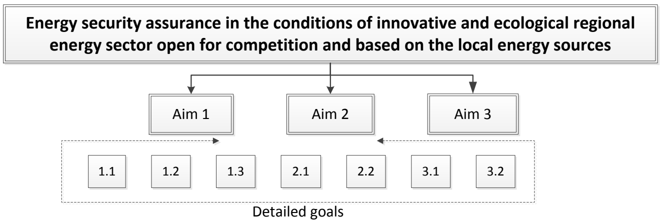


Fig.1, The method of building the energy strategy for Lower Silesia
Source: [6, pp. 18]



Legend: Aim 1 - Ensuring energy security; Aim 2 - The intensification of the innovation processes in the regional energy sectors; Aim 3 - The minimalisation of the effects on the natural environment and the introduction of the activities to economize the energy production and consumption; 1.1 - The energy security – current level; 1.2 - The energy security – medium – term level; 1.3 - The energy security – strategy level; 2.1 - The innovative research and implementation; 2.2 - The innovation – Smart Grids; 3.1 - Conducting the ecological actions in the energy sector; 3.2 - The efficiency of the demand side and of the suply side in the regional energy sector

Fig.2, The mission and aims of energy strategy for Lower Silesia
Source: [7, pp. 271]

2.3. Important theses according to experts' opinion

As it was mentioned above, the obtained results of the foresight research, based on Delphi surveys, allowed us to select seven sets of theses which:

- (1) are the most important for Lower Silesia,
- (2) support changes in the shortest period and influence the region to the greatest extent,
- support the realization regarding: (3) economic, (4) ecological, (5) social, (6) energy security, and (7) innovative scenarios.

Five theses were assigned to the 4 of the 7 sets above. They are:

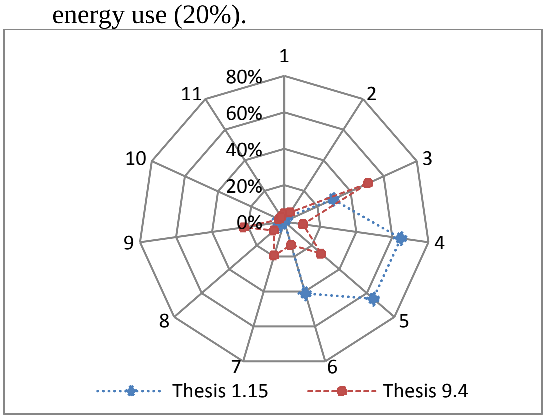
- Thesis 1.15[5]: There will be first attempts to extract the lignite localized near Legnica (a city in Lower Silesia).
- Thesis 7.2: The first small capacity nuclear reactor (10-40 MW) will be installed in Lower Silesia
- Thesis 9.4: 20% of electricity in Lower Silesia will come from scattered RES
- Thesis 13.1: The consumption of primary energy in the industry in Lower Silesia will decrease by 20% thanks to energy-saving processes.
- Thesis 13.3: The waste segregation technologies will be widely used.

Because the technologies based on fossil fuel and RES to produce electricity were chosen for quantitative analysis in this article, we should know what experts said about theses 1.15 and 9.4. 50% of experts indicated that thesis 9.4 could be achieved in the period of 2021-2030. 33% of respondents said it couldn't be comprehended until after 2030. The total costs of the implementation of this thesis are:

- the high cost of implementation proper (60%),
- the R&D cost (40%),
- high cost of living – exploitation (30%).

The benefits of the implementation of thesis 9.4 are (like on Fig. 3]:

- the growth of efficiency, production, transmission and distribution of energy (50%),
- the security of energy dispatch will improve (25%),
- saving fossil fuels (20%),
- the development of innovative processes related to energy use (20%).



Legend: 1 - Creating behaviours of economical energy usage; 2- The improvement of energy consumption efficiency by citizens (small consumers); 3 - The improvement of efficiency in producing, transmission and/or the distribution of energy; 4 - The growth of regional product; 5 - The improvement in the security of energy supply; 6 - The improvement in the access to energy; 7 - Saving fossil fuels; 8 - Achieving emission standards of CO_2, SO_x, NO_x and dusts; 9 - The development of innovative processes of energy use; 10 - Ecological education; 11 - The development of RES and distributed energy sources

Fig.3, Benefits of the realization theses 1.15 and 9.4
Source: The authors' concept

The main barriers to the realization of this thesis are the high costs of purchasing or/and implementing the technologies associated with the thesis (50 %).

The experts see thesis 1.15 as very important for Lower Silesia. More than 60% of experts pointed out this thesis as supporting energy security. 54% of experts indicated that this thesis could be achieved by 2020, and the next 23% in the years 2021-2030 predicted its completion. The last 23% of respondents say it couldn't be realised until after 2030. The cost of implementing this thesis includes:

- (very) high economic costs (73%),
- high social cost (73%),

[5] The number of the theses are the same as in original research.

- high environmental cost (84%).

The main benefits for the region relating to the implementation of this thesis are (Fig. 3):

- the growth of regional product (60%),
- the improvement in the security of energy supply (68%),
- the improvement in the access to energy (40%),
- the growth of efficiency in production, transmission and distribution of energy (20%).

The main barriers to the realization of thesis 1.15 are the introduction of new regulations connected with coal tax, the limits of greenhouse gas emissions and access to capital and the lack of following items: social acceptance for its realization, appropriate regulations (e.g. spatial development plans), the clear competences of local authorities in this range.

We can perceive that theses 1.15 and 9.4 are competitive to one another because thesis 1.15 supports the status quo and the interest groups related to conventional energy but the introduction of the 9.4 thesis changes the situation completely. On the other hand, they could be complementary to each other, and changes to the energy resources structure would be systematically made – the RES would replace fossil fuels.

2.4. Quantitative analysis – Logistic substitution model

Quantitative analysis was made based on the logistic substitution model (LSM) and IIASA *Logistic Substitution Model II* Version 0.9.87 application. The analysis was carried out for two kinds of electricity sources: independent RES and conventional power plants. The analysis was made for the value of electricity coming from generators located in Lower Silesia. The conventional power plants produce electricity mainly from lignite and coal, but recently from biomass as well. They also produce energy from wind farms and water turbines. The independent RES are alternative sources of electricity and we could match this situation to thesis 9.4. The availability of statistical data for Lower Silesia was the reason to choose these kinds of energy sources. The input data for the simulation was from 2000 to 2013. Nowadays, only slightly more than 2% of electricity is produced from independent RES in Lower Silesia. But we should remember that the significant part of Delphi experts said that 20% of electricity can be produced from independent RES.

Generally, a number of technology replacement processes as well as biological phenomenon, i.e. development of some kinds of population, show that these processes usually proceed in a similar way. Statistical data shows that in the first stage the researched variable increases at the same percentage rate each year. It is a typical situation for exponential function. After some period of time the increase becomes slower and slower. The growth function curves asymptotically and the curve has an S-shaped logistic curve. The LSM has some assumptions[6]:

- new technology (e.g. independent RES) enters the market and grows at logistic rates according to S-shaped logistic curve,
- declining technology fades away steadily at logistic rates uninfluenced by competition from new technology.

The logistic function is according to Eq (1):

$$N(t) = \frac{K}{1+e^{-\frac{\ln(81)}{\Delta t}(t-t_m)}}, \tag{1}$$

Where:
K – limit of growth
Δt – duration of time – the period needed for the $N(t)$ value to increase from 10% to 80% of K
t_m – midpoint, the period after which the curve (value of $N(t)$) reaches 50% of K

A transformed formula according to Fischer and Pry is often used to demonstrate the substitution of technologies. As a result of this transformation, the data is presented on a linear scale and it is not presented in absolute values. The Fischer-Pry transform (FP(t)) is like Eq (2) and Eq (3):

$$FP(t) = \frac{f}{1-f} \tag{2}$$

$$\ln(FP(t)) = \frac{\ln(81)}{\Delta t}(t - t_m) \tag{3}$$

Where:

$$f(t) = \frac{N(t)}{K} \tag{4}$$

Function $FP(t)$ is plotted on a semi-logarithmic scale and the S-shaped logistic is rendered linear. The effect of simulation for statistical data for Lower Silesia is presented on Fig. 4.

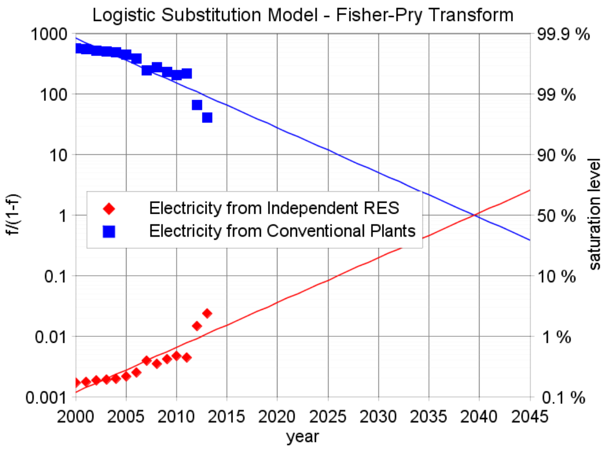


Fig.4, The substitution of researched sources of electricity production on Lower Silesia
Source: The authors' concept

[6] More information about the assumption of the LSM and models is presented in [2], [3].

The structure of electricity sources will be changed by 2039. Since 2039 more energy will be produced by independent RES and 20% of electricity will come from independent RES in 2033. The Δt equals 25 years and more than 8 months. When we compare the results of the quantitative methods (LSM) with the experts' opinion we can say that the regulation process supporting the development of RES should be more intensive in order to achieve 20% of electricity from independent RES.

III. THE STRATEGY IMPLEMENTATION PROSPECTS

The foresight research method made it possible to obtain a great deal of information and provided an opportunity to build a strategy proposal. Combining different research methods, data monitoring and making inferences based on quantitative methods enables regional authorities to modify instruments supporting the development of preferred technologies.

However, it should be noted that more than three years have passed since the completion of works on the Energy Strategy for Lower Silesia using foresight methods. This should have been sufficient for the assessment of conditions, opportunities and effects as well as the scale of the implementation of the strategy. In general, the scope and scale of the strategy implementation has been rather limited. However, to properly assess the causes of such situation and further potential of the use of the strategy it seems advisable to view the issue in three contexts, namely: international, national and regional.

3.1. THE INTERNATIONAL CONTEXT

In the international scene, particularly in Europe, there has been an increase of belief in the need to speed up the processes aimed at increasing the use of RES and maximization of the opportunities to increase energy efficiency. In general terms, one could venture a thesis that many EU countries are expressing the advisability or rather the necessity of energy transition that would result in re-industrialization processes through technological innovations allowing to carry out this transformation. The above thesis seems to be confirmed by the substantive and political content of the Transition to Energiewende conference in Berlin 23 – 26 March 2015 attended by dozens of ministers and deputy ministers of economy and energy management from many countries around the world. At the conference, both representatives of governments and of the academy expressed the need – necessity to transform the energy sector, including decarbonisation of energy processes.

Another conference to be mentioned here took place in Aberdeen; 7 – 9 July 2015, where scientists as well as economists from many countries were arguing for energy transition and the need to conduct research in the field of energy recovery processes (including the use of CCS), energy efficiency improvements as well as the social and economic impact of the changes occurring in the energy sector.

3.2. THE POLISH CONTEXT

Poland is a special country as far as its use of coal and lignite as primary energy sources is concerned. In terms of electricity production the share of coal is relatively very high (compared to other European countries) and amounts to about 90%. In Poland, the coal and lignite sector and the power generation sector using these two sources have been intensively developed since the fifties of the twentieth century. Some Polish regions (Silesia) and sub-regions such as the area of Bełchatów, Konin or Turoszów have lignite mines closely cooperating with power plants. It can be said that there is a kind of production monoculture in these regions. Hence, power and coal sectors have large political significance which under certain conditions can hardly be overestimated. As a result, the process of moving away from coal as the primary energy carrier is questioned in Poland and a number of significant bodies refer to the ideas resulting from the climate-energy package as if they were a kind of religion which does not necessarily have to be followed. This process is amplified by formal and institutional regulations. In fact, in Poland there is the phenomenon of regulation capture which consists in appropriating the regulation processes by the energy sector. As a result, it is difficult to find stimulators in Poland that would lead to a more extensive use of RES. It can be concluded that at present it will be difficult to find strong stimulants in Poland, including public support, for the intensification of the processes characteristic of the "energy transition".

3.3. REGIONAL CONTEXT

The Energy Strategy developed was clearly addressed to one of the 16 Polish regions, namely the region of Lower Silesia in the south-western part of the country. From the beginning of the strategy development the regional authorities have declared a keen interest in the document being prepared and to some extent supported the work on it. In Poland, local elections at the regional level are held every 4 years. The latest took place one and a half years ago. They brought a change of people in the authorities and a decrease of interest in energy policy in the region. As a result, the operational program for the region of Lower Silesia contained provisions which directly or indirectly referred to the Energy Strategy being developed. In this context the following aspects of the operational programme for Lower Silesia deserve special attention: the programme to improve energy efficiency, especially in the use of the buildings managed by local authorities and, to a limited extent, promotion of renewable energy installations. However, it can hardly be concluded that the region of Lower Silesia is prepared to fully implement intensive activities leading to the maximum use of the energy strategy discussed here or to the transformation of the processes of energy acquisition, transmission and consumption.

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Volume 2 (2015) issue 3, article 4

Comparison of different energy harvesting solutions for printed circuit board production

用于印制电路板生产的不同能量收集解决方案之比较

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Abstract - **For energy harvesting of thermal energy two well-known physical effects are usable, the thermoelectric and the pyroelectric effect. These two effects have been compared in literature in terms of their energy output and the applicability. In this contribution the two effects will be compared in the particular environment of the printed circuit board production. For applications without a thermal energy source the approach to use ambient radio frequency energy harvesting will be tested.**

Furthermore, we present the pure energy output information of the harvesters in the regarded environment, so that these results can be compared with other sensor systems. Our system consists of a temperature sensor, a microcontroller and a radio transceiver. The wireless interface enables a real-time sensor-data transfer.

The soldering process is one important focus of research in a PCB production environment (e.g. reflow oven) for our generators, because of the available thermal energy in this process. Nevertheless, the testing of a PCB in a climate test chamber is also a suitable application, since there is a cyclic change of low and high temperature. A thermoelectric generator (TEG) seems to be the best choice for the reflow oven, whereas for the test chamber application a pyroelectric generator (PEG) is preferred, because of the high temperature change. But in other processes where no temperature is involved the radio frequency energy harvesting. In our contribution we will focus on the questions. What is the best generator solution for the given applications?

Keywords - **Thermoelectric Generator, Pyroelectric Generator, Printed Circuit Board, Energy Harvesting, PCB-manufacturing, RF energy harvesting**

I. Introduction

In the printed circuit board (PCB) production the trend leads toward more and more complex designs, particular in Europe with small quantities and high quality demands. To achieve these requirements the new production cycles need to have a higher yield and a faster adjustment speed. A solution is to increase the numbers of sensors inside the production equipment, as well as place sensors inside the product itself (the PCB).

In section II some required fundamentals are explained. We focus on the embedded sensor idea, the thermal energy harvesting, the RF harvesting and the test environment. After the basics we present in section III, preliminary consideration of the possible harvesting methods, the pyroelectric and the thermoelectric one, in a chosen printed circuit board environment. In the fourth chapter the setup for the whole system is given with the required elements. For some elements like a microcontroller a firmware is required, which will be also described here. The results are shown in chapter V for the energy consumption of the hardware components with the firmware compared to the harvested energy with the preferred generator. In the last chapter a comparison is given with some future remarks.

II. Basic

In this section the fundamentals of the present paper will be shown. At first the embedded sensor principle, followed by the energy harvesting methods, which contain thermal energy harvesting and RF energy harvesting.

2.1. Embedded Sensor

The sensor inside the printed circuit board, as shown in Fig. 1, delivers information that can’t be measured from the outside or need to be manufactured manually at the PCB (increases time and cost), before the process. For example if the temperature at a solder pad should be tracked in a reflow oven. Today’s method is to attach a thermocouple near this solder pad and connect them with a wire to the data logger. The embedded sensor can be implemented near the pad and deliver information not only for the soldering process but also for the whole lifetime of the PCB.

Fig. 1, Embedded sensor in a PCB

2.2. Test Environment

The tests are done in PCB-manufacturing equipment. A reflow oven and a temperature test chamber were chosen for this paper. The reflow oven temperature (see Fig. 2) can be adjusted individually in four different heating zones, set to a common solder profile (maximum temperature 230°C).

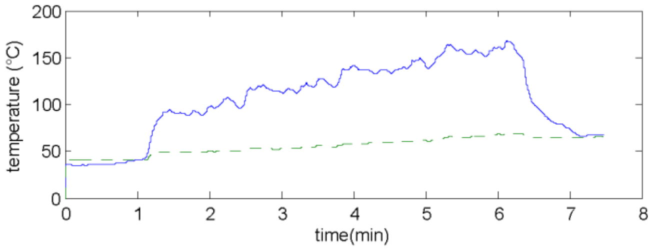

Fig. 2, Temperature of a device with heatsink in a reflow oven cold side (green) hot side (blue)

A temperature test chamber is used to test electronic components in terms of reliability by increased life cycle aging. This is done by changing the temperature inside the test chamber between 125°C to -40°C all 15 minutes. A temperature cycle is shown in Fig. 3.

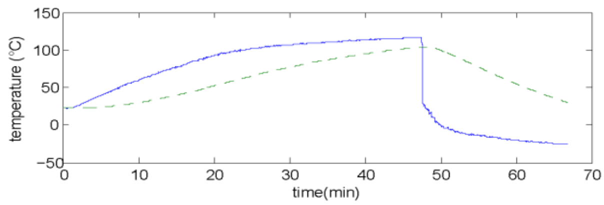

Fig. 3, Temperature of a device with heatsink in a temperature test chamber cold side (green) hot side (blue)

2.3. Thermal Energy Harvesting

The energy harvesters that are usable for the PCB manufacturing process are based on thermal energy and electromagnetic waves, because this energy can easily be archived at the manufacturing process.

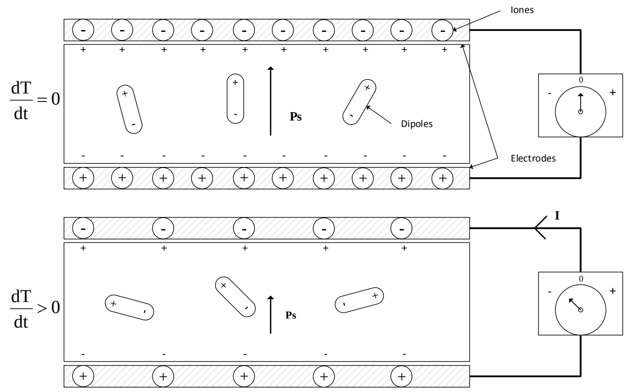

Fig. 4, Schematic principle of the pyroelectric effect

The thermal energy can be harvested by a thermoelectric generator (TEG) or a pyroelectric generator (PEG) [1], [2]. The TEG is based on the Seebeck-effect whereas the PEG utilizes the pyroelectric effect. A viable calculation for the energy generation of the PEG is shown in the following Eq. (1) from [3]:

$$I_{PEG} = \frac{pA\Delta T}{dt} \qquad (1)$$

The Eq. (1) is used to calculate the current with the pyroelectric coefficient (p), the area (A) of the PEG, with the orthogonal temperature flow vector and the temperature difference (ΔT) between hot and cold side of the PEG devide by the derivation of the time. The differential component implicits the energy harvesting as a gradient of the temperature difference (see Fig. 4), whereas a TEG requires a steady temperature difference. In Eq. (2) the voltage (V) of a TEG is calculated with the temperature difference and the Seebeck coefficient (α) [4]

$$V_{TEG} = \alpha_{AB}\, \Delta T \qquad (2)$$

2.4 EM-Wave Energy Harvesting

The electromagnetic energy harvesting or energy transfer can be done over a far distance to a transmitting device with an antenna setup or near distance with inductive coupling methods.

The available power in the far field can be described by Eq. (3), the power (dP) depends on the distance (r), the power of the transmitting device (P) and a defined Area (dA) of the antenna. The power level of a transmitter is regulated by country regulations, and can be set up to 25 mW equivalent isotropically radiated power (EIRP).

$$dP = \frac{P}{4\pi r^2} dA \qquad (3)$$

The available power decreases with the distance to the transmitting device. The decreasing factor depends on the distance definition: the power in a near field is proportional to 1/3r, whereas for a far field the ratio is 1/r. Therefore, the highest energy transfer is possible in the near field region, discussed in chapter 3.2. For the near field energy with an integrated circuit the NFC defined coupling mechanics can be used. In [5]–[7] inductive coupling is used to transfer energy over the air. A calculation for the energy transfer with known Q factors (Q_1, Q_2 of each coil) and the coupling factor (k) can be done with:

$$\frac{P_{rec}}{P_{tran}} = k^2 Q_1 Q_2 \qquad (4)$$

In Eq. (4) (P_{rec}) is the power of the receiver area, whereas (P_{tran}) is the power from the transmitter. This inductive coupling method can also be used to transfer the sensor information wireless, by adjusting the secondary coil load [5].

III. Energy Harvesting

There are wide varieties of methods and technologies under the term of energy harvesting. As before, we focus on available thermal energy harvesting in the PCB manufacturing process and easy to archive energy supply with RF energy harvesting methods. In this chapter simulations and preliminary considerations for the energy harvesting methods will be discussed.

3.1. Thermal

To compare the thermal energy harvesting methods, both are simulated with known and reliable parameters. The pyroelectric generator is based on the research described in [8]. The parameters for the simulation are given in Table 1.

TABLE 1, PEG simulation parameters

Unit	Value	Description
A	$1\ [cm^2]$	area
C_E	$1\ [\mu F]$	store capacitor
ε_0	$8.854e-12 [As/Vm]$	permittivity of vacuum
ε'	$14\ [As/Vm]$	real permittivity
d	$0.1\ [cm]$	thickness
p	$40\ [nAS/cm^2 * K]$	pyroelectric coefficient

As can be seen in Fig. 4, the energy harvesting of the PEG after 60 min is about 200 nWs. This harvested energy is simulated with a full bridge rectifier. The base equation for simulation of the voltage for each time step (n) with the parameters of Table 1 is

$$E_n = 0.5 C_E V_n^2\ ;\ V_n = \frac{pA\Delta T}{C_P + C_E} + \left(\frac{C_E \pm C_P}{C_E + C_P}\right) V_{n-1}. \qquad (5)$$

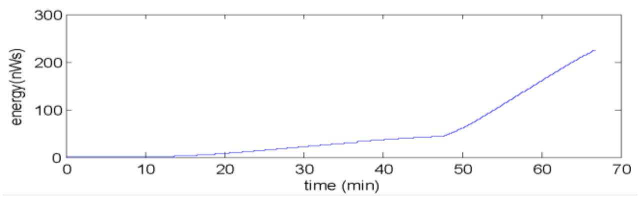

Fig. 4, Simulated energy output of the PEG in a test chamber

The TEG simulation on the other hand (Seebeck-coefficient of 0.03 [V/K]), with the same temperature curve as in Fig. 4, harvests an energy of about 40 Ws after 45 min. This could theoretical power the microcontroller about 50 times per second, based on the same energy consumption as mentioned for the PEG. This simulation proves the usability of a TEG to power the experimental setup, in theory.

3.2. RF-Harvesting

For the far field energy harvesting a spectrum of the commonly used frequency range was measured with a Wi-Fi device, Bluetooth and a proprietary solution transmitting at the same time (Fig. 5). The measured power at a range of one meter was about 0.0177 Watt, under ideal conditions in an experimental setup (no fading, reflection or absorption). These measurements are done with a spectrum analyzer, which improves the result, and not an energy harvesting circuit with antennas made in PCB-technology.

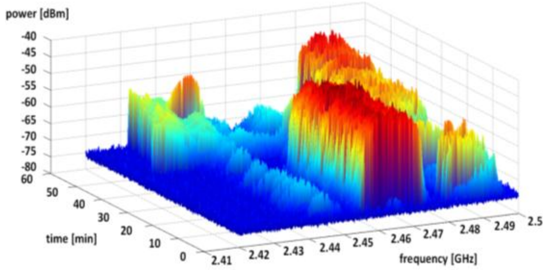

Fig. 5, Power density spectrum of the 2.4-2.5 GHz Band

As mentioned in [9] and [10] the efficiency of the radio frequency energy harvesting depends on the geometry of the antenna and requires a fixed frequency. The space for an antenna with high gain for 2.4 GHz is around 5-7 cm², with a maximum efficiency of 30% (2x2 Koch antenna array[10]). These requirements disqualify the far field energy harvesting for the given scenario of a PCB manufacturing environment, because the near field approach is usable with higher efficiency (80-90%). For another scenario to harvest over greater distances, this far field RF-harvesting may be the better choice.

The major advantage of the near field magnetic induction (NFMI) in the given scenario, is the possibility to power existing integrated circuits with the standardize method (NFC) at an efficiency of about 80-90% [5]. Therefore, the transmitting device don't need to be considered for the energy consumption calculation of the whole sensor system.

IV. Test Setup

4.1. Hardware

The hardware components are: a microcontroller (EFM32 Zero Gecko from Silicon Labs), a TEG (TEG 071-150-22 from thermalforce build of Bi_2Te_3) as energy harvester, a step up converter and power manager (LT3109 from Linear Technology) and for data transmission (TX) a low cost 433 MHz transmitter or a NFC device (RF430FRL152H from TI).

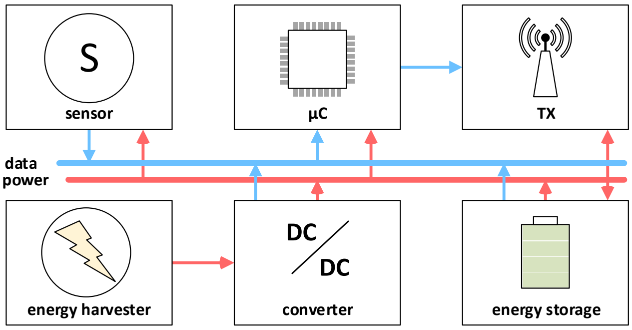

Fig. 6, Schematic hardware component setup

For the hardware components extra tests are done. For the microcontroller the energy consumption was measured with different firmware and used energy modes in combination with the 433 MHz transmitter. The TEG module was tested in a reflow oven with four heating zones and a test chamber for PCBs to compare the simulation results with real measurements.

The converter LTC3109 was tested with the TEG module together to compare the measurements taken with and without the integrated circuit converter. The big advantage of this converter in combination with a TEG, is the auto polarity feature what is useful when hot and cold side temperature changes, like in a test chamber. For storage a 470 µF capacitor was attached to the output of the converter.

For the experimental setup of the system some extra measurement devices are required. These are an oscilloscope (PicoScope 2205) and a data logger (globalPoint ICS). The oscilloscope measured the voltage at different point: the output of the TEG, the converter output, the current consumption of the microcontroller and the wireless transmitter. The data logger was used with thermocouple elements type K for temperature readings near the energy harvester and to verify the calculation software (described in the next chapter).

4.2 Software

The required software can be divided into the firmware for the microcontroller and the software that runs on a personal computer to enhance the sensor information.

The demands for the firmware are to use the highest power saving modes of the chosen microcontroller as often as possible . The other energy saving aspect in the firmware is the duty cycle of the sensor data gathering process. Particularly, when the 433 MHz transmitter is used wireless data transfer cycles. These two cycles depend on the requirements of the production equipment. For example, if they need the sensor data every second, the cycles must ensure this.

The software for the control PC requires analyzing the sensor information from the embedded sensor. Therefore, the position of the sensor must be known. Because, the structure of the PCB on top and below the sensor influence the measurement. Consequently, an exemplary tool is written in [11] to calculate the thermal parameters (the thermal time constant in particular) based on the layout file of the PCB under test. Three different geometries over the sensor, were tested (see Fig. 7): a sensor inside FR4 with copper on top (a), a thermal via attached to the sensor (b) and an IC over the sensor (c). For further development the integration of the calculated thermal parameter into the firmware is proposed.

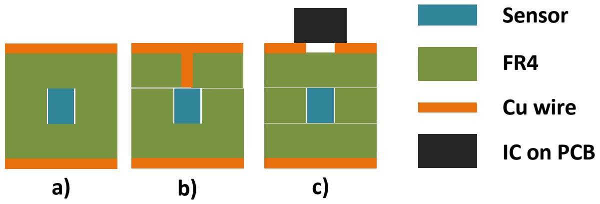

Fig. 7, Test-structure for the thermal time constant calculation

V. Results

The results start with the energy harvesting of thermal energy by a TEG. Therefore, Fig. 8 shows the harvestable energy inside a temperature test chamber. Table 2 shows the simulated Energy of the PEG and the measured one of the TEG for the both test environments. The PEG energy output in nWs area and can't be used for powering the hardware components.

TABLE 2, Thermal Energy Harvester by environment

Harvester	E_{PEG} [mWs/min]	E_{TEG} [mWs/min]
Reflow oven	$16e-6$	800
Test chamber	$200e-6$	330

The TEG on the other hand has an energy output of mWs, this can be used to power the required electronic components of the test setup. Therefore, the TEG was connected to the converter to test the combination of both.

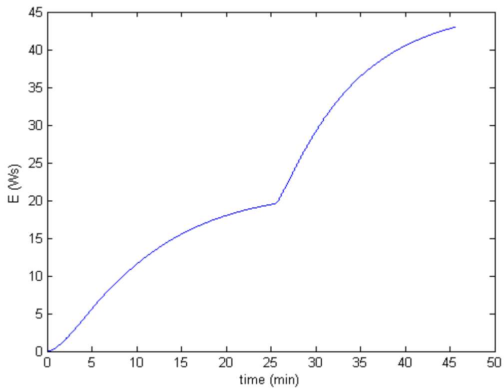

Fig. 8, Energy of a TEG in a temperature test chamber

In Fig. 9, the Voltage of the TEG with the connected converter in a reflow oven is shown. The blue curve displays the voltage at the output of the converter and the green one the voltage of the output of the TEG. The converter has a minimum voltage of 50-100 mV (depending on the used transformer ratio). The figure shows that the voltage of the TEG in a reflow oven is sufficient for the converter to power itself and load a 470 µF capacitor at the output.

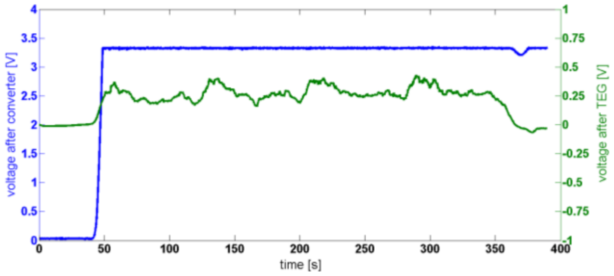

Fig. 9, Voltage of the TEG with the connected converter in a reflow oven

To check if the energy harvesting of the TEG in the tested environment is enough to power the sensor and the microcontroller some measurements are done, with the power consumption. In Fig. 10 the current consumption is shown for three different firmware cases:

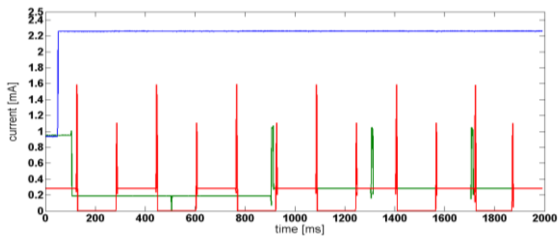

Fig. 10, Current consumption of the microcontroller with a 433 MHz transmitter - blue: always online – green: cycle 400ms & low power mode –red: cycle 200ms & ultra-low power mode

The blue curve shows the power consumption of an always on-line mode then in green an optimized low power mode with 400 ms cycle time is given, at least the red curve describe the ultra-low power mode with 200ms cycle time. The 200 ms are chosen to show that the mode consumes less power even if it has a higher duty cycle (DC). Table 3 shows the average energy consumption calculated with 3.3 V supply voltage.

TABLE 3, POWER CONSUMPTION OF THE MICROCONTROLLER WITH DIFFERENT FIRMWARE

mode	P_{avg} **[mW]**	P_{peak} $[mW]$
always one-line	7.3	7.5
low-power 400 ms DC	0.9	3.3
ultra-low-power 200 ms DC	0.6	5.2

The results of the software, to calculate the thermal parameter for an embedded temperature sensor, are shown in the following table 4. The values are considerably different from each other, which leads to different sensor information in terms of temperature depending on the structure. The heat flow is 100 times faster with a via attached to the sensor in comparison to bare FR4 in the way. The results demonstrate the gap between the structures, but require calculation for each layout independently.

TABLE 4, CALCULATED TIME CONSTANT FOR DIFFERENT STRUCTURES ABOVE THE SENSOR

structure	τ_{calc}**[s]**
FR4+Cu	4
with IC	32
with Via	0.005

VI. Comparison

We showed in this paper that a TEG as an energy harvester for an embedded sensor in a PCB within the PCB-manufacturing environment can be used. The PEG was not sufficient. For applications without thermal energy an energy harvester based on the RF harvesting can be used. In particular a near field inductive coupling method is preferred, because this energy concept is able to send the sensor data and the energy consumption of the transmitting device omitted.

In conclusion, the use of a TEG as a primary harvester to power the sensor and the microcontroller in a thermal environment is a suitable approach for this scenario. When it comes to data transmission a NFMI method has the advantage over a normal radio transmitter, because the power will be delivered from the receiving device and can lead to a NFMI powered solution of the whole sensor system.

The used microcontroller requires a firmware to ensure minimum power consumption. The results show that the best configuration for a cycle of about 1 s requires 300 µW (with peaks of 5.3 mW). With this setup a TEG will be enough to power the system. The PC software calculations prove that it is required to take this parameter dependency into consideration, because of the difference (factor 100) between the structures.

The future work will focus mainly on creating the whole system with an NFMI and a TEG as power supply. Also, different sensor types have to be evaluated, which will give additional information about the production process and the life time monitoring of a PCB product. Also the interaction of calculations in the layout phase, like the thermal parameter calculation and the placement with the microcontroller of the sensor system, and the control PC of a manufacturing process with these informations, will require further research and tests.

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Hydrogen adsorption on fluoro-graphene: an estimate by simulation

氟石墨烯之上的氢吸附：仿真估计

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Abstract - **An estimate of the fluoro-graphene adsorption capacity for hydrogen is determined by Monte Carlo numerical simulations. Structure and symmetry of the atom arrangements in fluoro-graphene have been estimated by experiments and ab-initio computations. A comparison of effective and ab-initio potential for gas adsorption on fluoro-graphene materials is done before mesoscopic simulation setting up. These data allow to determine by ab-initio calculations the molecular interactions between gas molecules and the functionalized graphene materials or to estimate approximate effective atom-atom potentials to describe them. In this work on the basis of computed and effective interactions we calculated the fluoro-graphene adsorption properties of hydrogen up to high pressure both at room and low temperature. The estimation of hydrogen storage at 77K on fluoro-graphene is around 9 *wt*%.**

Keywords – **fluoro-graphene, DFT, Monte-Carlo simulations, hydrogen storage, physisorption.**

I. INTRODUCTION

The adsorption of molecular gas by carbonaceous and porous materials has been studied extensively in the literature [1,2]. Indeed, numerous experimental and theoretical works have established that these materials have excellent adsorption properties which are optimal when the surface adsorption per gram is maximal and the pores have a nanometric size [3]. For pure carbon adsorbents, this maximal surface is obtained when the pore walls are made by a single basal graphite plane, *i.e* graphene. Such a type of pores corresponds also to a quasi-maximal strength of attractive interaction between the walls and adsorbed gases since, due to the short range of the van der Waals interactions involved in solide-gas physisorption, a wall made by two or more graphite planes has an interaction very close to that generated by a graphene wall [4]. The van der Waals interaction of one carbon atom in graphene sheet being weak, attempts have been done to increase the adsorption capacity of porous carbons by grafting atoms or molecules on the external graphene plane of pores [5,6]. The functionalized carbon atoms are expected to improve the attractive interaction of graphene on adsorbed gas molecules. However, the superficial density of grafted atoms or molecules is often small and the molecular mass of grafted molecules can decrease the adsorption capacity expressed in term of weight percent an important parameter characterizing the ability of an adsorbent to be used in mobile storage devices. In order to overcome these shortcomings, fluoro-graphene materials, in which each carbon atom is grafted by a fluorine atom, have been developed. For this material the functionalization is maximal: one fluorine atom per carbon atom and the decrease of the weight per cent possibly should be compensated by the increase of the van der Waals attraction of the grafted graphene. It is the main aim of this work to determine to which extent a noticeable improvement of the graphene adsorption capacity can be expected from the functionalization by fluorine. This estimate is performed by Monte-Carlo (MC) simulations in the the grand canonical (GC) Gibbs ensemble. Such computations to be reliable need to be performed with realistic modeling of pores and interactions between adsorbed gas molecules and the functionalized graphene surface. The adsorbent model used in the simulation is described below and one possible approach for describing the interactions is discussed. The simulation data are given for the hydrogen adsorption in porous fluoro-graphene materials. A conclusion summarizes the results of the work.

II. Calculation method

II. 1. Quantum chemical calculations

Quantum chemical calculations were performed in the frame of periodic DFT by means of the Vienna *Ab initio* Simulation Package (VASP 5.2.11) [7,8]. The electron-ion interactions were described by the projector augmented wave (PAW)[9,10] method, representing the valence electrons, as provided in the code libraries. The convergence of the plane-wave expansion was obtained with a cut off of 500 eV. The generalized gradient approximation (GGA) was used with the functional of Heyd-Scuseria-Ernzerhof (HSE06) [11, 12]. The sampling in the Brillouin zone was performed on a grid of k-points separated by 0.1 $Å^{-1}$ for the geometry optimizations. To improve the ability of DFT calculations to describe the weak interaction, especially the dispersion interactions, Grimme et al.[13] proposed to introduce an empirical correction of dispersion contribution to the standard density functional (denoted as DFT-D); using this strategy, the estimation of noncovalent interactions can be computed very accurately at the DFT level. All the computations reported in this paper are performed using the dispersion-including DFT Grimme D2 method. DFT-D2 Grimme (G, D2). This method describes the dispersion interactions between a particle and its neighbours in a given radius, via a simple pair-wise force field summed to the pure DFT energy.

$$\Delta E = E_{DFT} + E_{D2} \qquad (1)$$

The FG (fluoro-graphene) substrate is modelled as a slab, where a unit cell is periodically reproduced in the 3D space. In this approach the surface is infinite in two dimensions (in x and y directions), with a vacuum space (38 Å) in the z axis direction. This vacuum space should be large enough to enable the hydrogen adsorption and disable its interaction with the consecutive repetition of the system slabs. In the present case, the slabs representing a (2 × 2) supercell of armchair GF were built from optimized unit cell (See Fig 1.), using Modelview software[14]. The primitive unit cell parameters are: a=2.59Å, b=2.59Å, $\alpha=\beta=90°$ and $\gamma=120°$, being in a good agreement with previous experiment and theoretical results [15-19].

II. 2. Adsorbent model

In the simulations where the nanometric scale of the pore network is specifically considered, a good approximate model for the pore shape is a slit with planar walls that, in this work, will be fluoro-graphene planes. The arrangements of functionalized carbon atoms in fluoro-graphene have been studied by *ab-initio calculations* [20-21]. These studies allow defining an approximate reliable model of the quasi bi-dimensional structure of these materials. In our computations, we have chosen to use a chair conformation of the carbon atoms rings that has been identified strongly stable by the DFT computations. In this conformation, the carbon atoms are distributed equally in two parallel planes distant by 0.45Å. In a plane, the C atoms are arranged on a triangular lattice, but their two nearest neighbors are located in the other plane at a distance of about 1.53Å. The bond linking the C atom to the F atom is pointing outside the plane external faces and its length is equal to 1.40Å. The structure of the adsorbent model is fully defined by the choice of the slit width that, at the considered nanometric scale, is optimal for 1.0 − 2.0nm taking into account the size of adsorbed gas molecules and the van der Waals interactions range.

A simple, but approximate, way to describe the interactions between gas molecules and an adsorbent surface is to associate to molecules and adsorbent atoms a pair potential. This way is widely used in the literature on the basis, for instance of Lennard-Jones (LJ) pair potentials:

$$v_{ij}(r) = \epsilon_{ij}\left[\left(\frac{\sigma_{ij}}{r}\right)^{12} - \left(\frac{\sigma_{ij}}{r}\right)^{6}\right] \qquad (2)$$

where i and j correspond to a specific site or atom in molecules or the adsorbent. The parameters ϵ_{ij} and σ_{ij} are in general obtained empirically by systematic comparisons with experimental data or derived from the Berthelot rules

$$\epsilon_{ij} = \sqrt{\epsilon_i \epsilon_j} \text{ and } \sigma_{ij} = 0.5(\sigma_i + \sigma_j) \qquad (3)$$

where ϵ_i or ϵ_j and σ_i or σ_j are the parameters of LJ potentials defined for the atoms or molecular sites i or j and considered transferable and usable to estimate the cross-interaction ij. Such an interaction potential between hydrogen and fluoro-graphene has been used in ref. [22]. The empirical parametrization of the van der Waals interaction $v^W_{H_2 F_g}$ between H_2 gas molecule and fluoro-graphene solid is made on the basis of a contribution of C and F atoms.

$$v^W_{H_2 F_g} = -\sum_i \frac{C6C}{r_i^6} - \sum_j \frac{C6F}{r_j^6} \qquad (4)$$

where r_i and r_j are respectively the distance between the center of mass of H_2 molecules and the C and F atoms, the coefficients *C6C* and *C6F* being equal to 9.96 eV°A^6 and 16.38 eV°A^6. It is possible to calculate ϵ LJ effective parameters corresponding to C and F atom inside the fluoro-graphene framework using the Berthelot rules. The values of σ LJ parameter estimated in the literature [23] are equal to 3.4°A for C and 3.0°A for F. The ϵ effective value for C is 21.3K which is close from a standard value equal to 28.0K used for adsorption simulation in graphene [24]. The ε effective value for F is 125.9K and can be compared to previous estimates given for instance in ref. [25]. From these values of ϵ and σ, effective LJ potentials for C and F are obtained and summarized in Table 1.

The H_2 LJ potential is localized on the molecular center of mass and is associated with three charges to take into account the linear molecular electric quadrupole: one charge −2q at the center of mass and two charges q localized symmetrically on the molecular symmetry axis at 0.37nm of the center of mass.

TABLE 1, Parameters of empirical LJ potentials for H_2 molecule, C and F atoms of fluoro-graphene. ϵ is in unit of Kelvin degree, σ and distance in unit of nanometer, and electric charge q in unit of the electron charge. Cross-interactions are obtained from the Berthelot rules

LJ parameters	ε	σ	q charge
H_2 molecule	36.7	0.2958	0.480
C of fluoro-graphene	21.3	0.3400	
F of fluoro-graphene	125.9	0.3000	

III. RESULTS AND DISCUSSION

In figure 1, the full DFT interaction between hydrogen and a fluoro-graphene plane is given at HSE0 level. The variation of the interaction potential in xy plane is shown on Figures 1-b-d. Figure 1-a shows the variation of the interaction potential when hydrogen molecule is located above one carbon atom, just between two fluorine atoms. The position of molecule is set in a position for which the axis of hydrogen molecule is perpendicular to the surface.

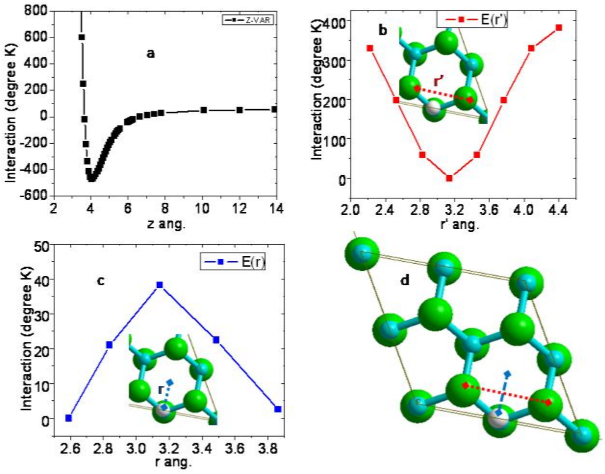

Fig.1, HSE06-D2 interaction between H_2 and fluoro-graphene toward z axis (a) and xy plane (b and c). The structure of the chosen supercell showing the hydrogen molecule displacement directions in xy plane (d).

One can observe that the minimum of the interaction along z axis is found to be equal to -470K with an equilibrium distance of 4.05Å from the surface. The variation of the interaction in xy plane reaches 340K and the hydrogen most stable position is found to be locating in a bridge between two fluorine atoms. The total interaction can decrease down to -800K depending on the position in xy plane. Previously, the minimum interaction energy was found to be equal to -677K at PBE-D2[20] level and the equilibrium position was found between two fluorine atoms. Using Moller Plesset method a minimum interaction energy of 349 K was obtained by Reichenbächer et al.[26]

In figure 2, the full effective interaction between hydrogen and a fluoro-graphene plane is given. The contributions to this interaction of the C and F atoms are also plotted. The minimum of interaction is equal to about -620K and is located at 4.8Å from the fluoro-graphene plane. The interaction value is greater than the HSE06-D2 value (-470K) due probably to the parameter significantly different for fluorine.

The equilibrium distances are also different of about 0.75Å and the interaction becomes repulsive fewer than 4.05 and 4.80Å for the effective and DFT potentials, respectively.

The figure 3 shows that, when the contributions of the two walls are added, in the central part of the smallest pore the interaction minimum is equal to −1100.0K.

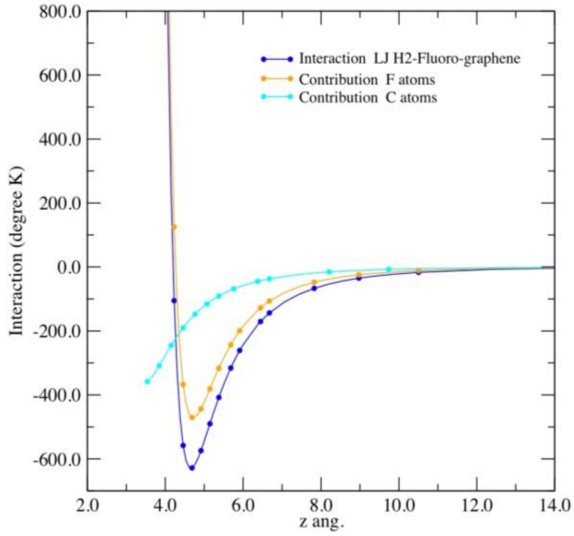

Fig.2 Effective interaction between H_2 and fluoro-graphene expressed in kelvin (K)

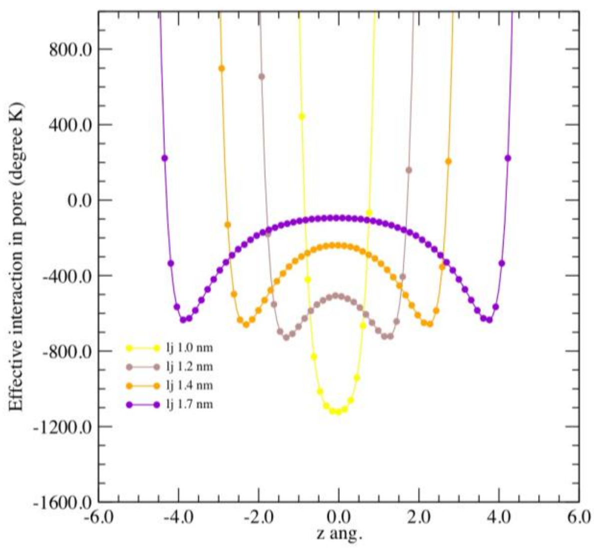

Fig. 3 Interaction of H_2 expressed in kelvin (K) molecule inside pores of different widths with fluoro-graphene walls.

In figure 4, the molecular simulation results for the excess adsorption are given. The excess adsorption is defined as the difference between the total adsorption and the adsorption due to the compression, *i.e* the gas amount which, in any case, would be inside the pore volume in the absence of a molecule-wall interaction.

In the small pore of width equal to 1.0 nm, when the pressure increases, the excess adsorption is maximal around 200bars and, for larger pressures, it does not increase due to the steric effects between adsorbed molecules. For larger pores (widths equal to: 1.2, 1.4 and 1.7nm) the excess adsorption increases up to 500bars, but is larger for the width equal to 1.4nm because the inter-molecular steric effects are reduced compared to the case of the smallest width and the interaction between the gas molecules and pore wall is stronger than in the larger pores (cf. fig. 3).

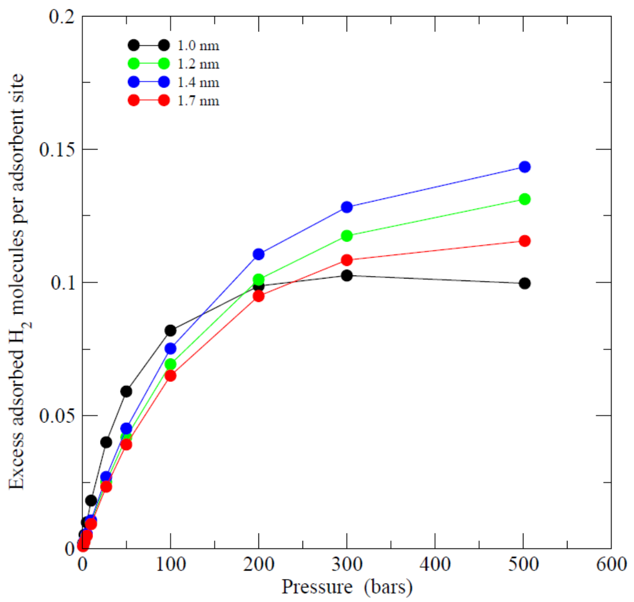

Fig.4 Excess adsorption of H_2 molecule per site at 293.16 K. A site is defined as one C atom of the fluoro-graphene plane. The ratio between the excess weight per cent and the excess adsorption per site is equal to 6.45.

The estimation of hydrogen storage at 77K on fluoro-graphene is around 9 *wt*%, higher than the pristine graphane (5 *wt*%) estimation and more close to the values found for graphane doped by sodium (10.3 *wt*%) or lithium (12.3 *wt*%)[27] ; values to be compared to the DOE target [28].

IV. Conclusion

The adsorption properties of the fluoro-graphene for H_2 at room temperature have been determined using an effective interaction and compared with DFT calculations. In the case of graphane where such a comparison is being done, a good agreement is obtained [29] between the adsorption estimated from the effective and theoretical interactions. Such a result reinforces our confidence that the present estimate of the adsorption capacity of fluoro-graphene is reliable. The adsorption of H_2 on fluoro-graphene expressed in excess weight per cent is not significantly different from that of graphene being equal to ~ 1.0% at high pressure and room temperature [3, 29].

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