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LABORATORY OF NUCLEAR INSTALLATION SAFETY

IAEA COORDINATION RESEARCH PROGRAM
"Development of Small Reactors without On-Site Refueling"

Report of the Second Working Year

Economic Benefits of Revising the Need for Relocation and Evacuation Measures Unique to NPPs for Innovative SMRs for Regions with Electricity Co-Generation

IAEA Research Contract No. LIT13092

Dr. habil. J. Augutis

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TATENA KOORDINUOJAMA TYRIMŲ PROGRAMA
"Development of Small Reactors without On-Site Refueling"

Antrųjų metų ataskaita

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Habil. Dr. J. Augutis

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Summary: This report include the following: 1) Review the curent licensing regulations in Lithuania, and specifically the emergency response planning for the NPP Ignalina considering technical basis (demography); 2) Update a study of the economic impact of revised licensing requirements on district heating; 3) Update meteorological data, based on available databases necessary for analysis of one selected site (Ignalina NPP).		
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LIST OF ABBREVIATIONS

ALWR	Advanced Light Water Reactor
CCGT	Combined Cycle Gas Turbine
CHP	Combined Heat and Power Plant
DH	District heating
HOB	Heat Only Boilers
CRP	Co-ordinated Research Project
EPRI	Electric Power Research Institute
EPZ	Emergency Planning Zone
FP	Fission Product
FPZ	Flight Prohibition Zone
GIF	Generation IV International Forum
HPSPP	Hydro Pumped Storage Power Plant
IAEA	International Atomic Energy Agency
INPP	Ignalina Nuclear Power Plant
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
IRIS	International Reactor Innovative and Secure
LEI	Lithuanian Energy Institute
LPZ	Longer Term Protective Action Planning Zone
NEI	Nuclear Energy Institute
NPP	Nuclear Power Plant
NRC	U.S. Nuclear Regulatory Commission
PAZ	Precautionary Action Zone
PP	Power Plant
PRA	Probabilistic Risk Analysis
PSA	Probabilistic Safety Analysis
SMR	Small and Medium Reactor
SPZ	Sanitary Protection Zone
TPP	Thermal Power Plant
UPZ	Urgent Protective Action Planning Zone
USA	United States of America
VATESI	Lithuanian State Atomic Energy Safety Inspection

INTRODUCTION

Small and Medium Reactor in general are of interest to International Atomic Energy Agency member countries since they enable introducing new generating capacity at a rate matching the consumption increase rate and by its size limit financial risks. Moreover, they may be the only viable option for smaller and/or developing countries, due to limitation imposed by the grid size and available financial resources. Innovative SMRs with no on-site refueling (or, with refueling at infrequent intervals) are of special interest, since they enhance safety and proliferation resistance.

However, new approaches are needed to overcome the traditional economy of scale and make SMR economically attractive. These include:

- modularity, production in series, pre-fabrication;
- new features, e.g., passive safety systems leading to design and construction simplicity;
- no on-site (or infrequent) refueling, reducing operational and maintenance costs;
- enhanced licensing, with revised siting requirements, that improves operational and economic performance.

While relying on all these features, this work specifically focuses on the last one, addressing the objectives specified in the Agency's CRP on innovative SMRs with no on-site refueling, as well as the CRP on Identification of competitive technological options for SMRs.

Current regulations relevant for NPPs and their siting require "that adequate protective measures can and will be taken in the event of a radiological emergency." This requirement has been further interpreted in the USA (in 10CFR50.47) as a requirement for emergency planning in an area with a 10 miles radius, i.e., extending far beyond the site boundary. This prescribed 10 miles radius is the same for all NPPs. Historically, it was selected to very conservatively envelop all designs, but it does not include provisions to account for significant safety improvements achieved since.

The emergency planning requirement may pose a significant burden on plant owner (utility), both in the construction and in the operation phase. During construction, it may be necessary to build infrastructure (highways) to comply with the requirement. During operation, it is necessary to maintain an evacuation capability in a relatively wide area. Moreover, for all practical purposes it freezes any human development in a large area around the plant, a burden for small countries and/or areas with significant growth. Finally the fact that the off-site zone around NPP is treated in a special way sends an incorrect message to public regarding the safety of NPPs.

The advanced and safer reactor designs further reduce risk to public, and should therefore offer a possibility to reduce or eliminate some of the emergency plan and evacuation requirements. This need was identified by the Agency (INPRO [10], User Requirement "The innovative nuclear reactors and fuel cycle shall not need relocation or evacuation measures outside the plant site, apart from those generic emergency measures developed for any industrial facility") as well as by the Generation IV International Forum (GIF) [5]. It is deemed possible to reduce emergency-related site requirements for advanced plants, while at the same time providing a protection to general public equal or better than that provided by the current generation of NPPs and current regulations.

Achieving licensing with this new objective would offer significant societal and economic benefits to member countries, general public and plant owners/operators, including:

- increased public acceptance of nuclear power, since they will be treated as any other industrial facility;
- reduced need for infrastructure, thus reducing cost;
- reduced operational costs;
- enabling co-generation application, including district heating and desalination, where the plant cannot be located remotely from the intended user;
- enable siting that would reduce transmission costs;
- enable wider choice of siting locations in countries with relatively high population density.

In summary, achieving licensing with no need for emergency plan and evacuation measures will improve viability of deploying new NPPs, and is of particular importance for small and medium reactors, whose competition with larger plants is impaired if burdened by the same additional infrastructure and operational costs.

The aim of this report is to contribute toward the presented overall objective, using as a testbed the design of IRIS (International Reactor Innovative and Secure), as a representative innovative light-water SMR with option for infrequent on-site refueling, with the ultimate goal of developing a technology-independent approach.

BACKGROUND

During the past 30 years, the possibility of reducing or eliminating the EPZ has been subject of various efforts. In 1985 and 1986, the licensees for the Calvert Cliff and Seabrook power stations petitioned the NRC for a reduction of the EPZ requirement. These petitions were rejected for lack of technical detail. During the following 30 years the NRC issued various papers dealing with the definition of emergency planning procedures for evolutionary reactors. In recent years, studies from EPRI and NEI have directly addressed this issue. In TR-113509, EPRI documented [8] a set of probabilistic and deterministic studies to show that a significant reduction in the EPZ radius was possible for ALWR while maintaining the same level of safety of existing plants. In NEI-02-02 [18], NEI proposed a complete risk-informed revision to NRC 10CFR50 document, in which the need and extension of the EPZ would be based on purely probabilistic considerations. Outside the US, similar activities have been ongoing: just to make an example, a social and technical study on the possibility of reducing the EPZ for the APR-1400 was performed in Korea.

Presently, IAEA/INPRO [10] and GIF [5] have identified the need for licensing that would allow reducing emergency planning requirements, but we are not aware of any on-going work.

At the moment, no advanced SMR in either the design or development stage is actively considering elimination of the no emergency response requirement, with the lone exception of IRIS [16]. Thus, the approach that may be developed for IRIS under this program would become available to serve as a roadmap for similar initiatives by other advanced designs [15].

Lithuanian Energy Institute, as a member of an international team, is involved in developing IRIS, an innovative light-water Small/Medium size reactor. Among its innovative design features, of particular importance is the enhanced safety achieved through the IRIS Safety-by Design™ philosophy. Additionally, IRIS core design includes capability for a significantly extended reloading cycle, resulting in infrequent refueling. One of the IRIS project aims is to license the reactor with a revised (reduced or eliminated) need for relocation and evacuation measures. This would result in no off-site emergency planning requirements, or at least in a significantly reduced planning zone. Preliminary considerations of this objective have been initiated within the IRIS team, thus offering excellent synergy with the corresponding INPRO objective. Combined with its characteristics (innovative SMR with option for infrequent refueling), IRIS presents a very suitable testbed for examining means, methods and approaches to revise evacuation requirements and for evaluating impact (benefits) should such a change become possible.

LEI, as a member of the IRIS team, is involved in PRA analyses, including those related to external events. Additionally, LEI is actively participating in establishing design solutions for IRIS to enable effective implementation of co-generation for district heating.

1. THE EMERGENCY RESPONSE PLANNING IN LITHUANIA

The task of review the licensing regulations in Lithuania, and specifically the emergency response planning for the Lithuanian nuclear facilities (e.g. NPP) is identification of changes which would be necessary if the emergency planning for the future power plants is to be eliminated or reduced. At present state the current practise is analysed in this report.

1.1. Current National Practice in Lithuania

The general objectives of emergency planning are to: prevent serious deterministic health effects and reduce the likely stochastic health effects of ionising radiation (cancer and other radiation-induced cases). In case of a radiological accident (due to internal or external events) in a nuclear power plant, in enterprises and facilities using nuclear sources, transporting radiological materials, the territory may be contaminated by radioactive substances. In order to evaluate the extent and consequences of radiological contamination in detail, the National emergency response plan is currently usually singled out from the rest of emergency response action plans. It gives a comprehensive description of possible consequences and actions of civil protection institutions and the population during the general accident. However, for the future licensing we need to promote enhanced licensing that should treat risk due to NPPs in the same way it is treated for other industrial facility.

As an example of the current regulation and planning, in the National emergency response plan of Lithuania, in the event of a radiological accident at a NPP, provided measures become operational as soon as the accident happens and when radioactive substances are spread or may be spread beyond the boundary of the NPP sanitary protection zone.

This Lithuanian plan provides means of protecting the population, their scope, terms, assignment of responsibilities, and implementation procedure. The plan is needed for organisation and co-ordination of actions taken over by ministries, other State Administration institutions, county and local municipal authorities for taking protective measures for arrangement of immediate response actions, for the operative notification of neighbouring countries of a nuclear accident or radiological emergency.

For the accident types, emergency response takes place over two distinct areas: sanitary protection zone and the area beyond the sanitary protection zone. Sanitary protection zone (SPZ) means the area surrounding the facility, which is under the immediate control of NPP in Lithuania.

The area beyond the sanitary protection zone is divided into three main zones: Precautionary action zone (PAZ), Urgent protective action planning zone (UPZ), and Longer-term protective action planning zone (LPZ). Precautionary action zone (PAZ) goal is to substantially reduce the risk of deterministic health effects of ionising radiation before radionuclides emission into the environment. Urgent protective action planning zone (UPZ) means a predesignated area around the facility where a plan for urgent protective measures is made in advance. Longer term protective action planning zone (LPZ) means a predesignated area around the facility farthest from the facility and including the urgent protective action planning zone. It is the area where the actions to reduce the long-term doses from deposition and ingestion should be developed in advance.

These zones are roughly circular areas with NPP in the centre. The size of the zones (see Table 1) in Lithuania has been determined by an analysis of international practice.

Table 1. The Size of Controlled Zones

Name of the Zone	Sanitary protection zone (SPZ)	Precautionary action zone (PAZ)	Flight prohibition zone (FPZ)	Urgent protective action planning zone (UPZ)	Longer term protective action planning zone (LPZ)
Distance from NPP	3 km	5 km	10 km	30 km	50 km

In IAEA-TECDOC-955 [11] and IAEA-TECDOC-953 [12] there is recommendation regarding the size of PAZ, UPZ and LPZ. The basis that leads to selecting these limits is mainly deterministic; however some risk related considerations are involved too.

The size of the *PAZ* is based primarily on the following considerations:

- Urgent protective actions taken before or shortly after release within this zone will *significantly reduce the risk of dose* and *prevent doses above the deadly threshold* for the most severe accidents at the NPP;
- For atmospheric release under average meteorological conditions this zone covers the distances where about *90% of the off-site risk of serious deterministic health effects could occur.*

The size of the *UPZ* represents a judgment on the extent of detailed planning which must be performed in order to ensure effective response. The zone should cover the distance where about *99% of the off-site risk of serious deterministic health effects could occur*. In particular emergency, protective actions, measures might well be restricted to a small part of UPZ. On the other hand, for the worst possible accidents, protective measures might need to be taken beyond the UPZ. The UPZ is the area where preparations are made to promptly perform *radiation monitoring* and implement urgent protective measures based on the monitoring results. Such as plans and capabilities *to implement sheltering, evacuation and distribute thyroid blocking iodine;* they reflected the fact that evacuation could be required up to the boundary of the UPZ (reception centers for evacuation are sited outside the zone).

The size of the *LPZ* represents an area where preparation for effective implementation of protective actions to *reduce the risk of deterministic and stochastic health effects from long term exposure* to deposition and ingestion of locally grown food should be developed in advance. The LPZ area covers distances where about *99% of the off-site risk of dose above generic intervention levels could occur*. More time will be available to take effective action within this zone; in general, protective actions such as *relocation, food restrictions and agriculture countermeasures* will be based on the radiation monitoring and food sampling.

As the zones can be defined only for national therritory (in spite that the NPP can be located near the border of country), in Lithuania UPZ and LPZ are evenly divided into 16 sectors, with the starting point from the geographical co-ordinates of the NPP. The angle of every sector is equal to 22,5 degrees. Each sector in its turn is further sub-divided into 6 segments: 3-5 km, 5-10 km, 10-15 km, 15-20 km, 20-30 km, 30-50 km from NPP.

The international co-operation of the Republic of Lithuania in the sphere of civil protection is based on universally recognised international principles of civil protection, human rights protection, environmental protection and common welfare following international treaties and other legislative acts. In case of a radiation accident in NPP, the Civil Protection Department shall immediately notify neighbouring countries on the incident and its expected consequences.

Information on the occurrence of the radiological accident or the exceedance of radiation in the Republic of Lithuania is passed to foreign countries and international organisations in the manner and size as required by the 1986 IAEA Convention On Early Notification of a Nuclear Accident in accordance with Governmental Regulation No 972 “On the Accession to the 1986 Convention On Early Notification of a Nuclear Accident” dated on 13 October 1994. To enforce the requirements of this resolution, in the event of a nuclear accident in the NPP, the Ministry of Environment shall present to the regulatory body (VATESI) current and forecasted hydro meteorological information, results of environmental gamma monitoring, on-going and planned radiation protection measures beyond the area of the sanitary protection zone, the expected time of the release of radioactive substances into the environment. The Radiation Protection Centre presents to VATESI the information on ongoing or planned population protection measures.

In case of a nuclear accident due to internal or external events, in its turn VATESI shall provide the IAEA and, directly or through the IAEA, the neighbouring countries, with which bilateral or multilateral co-operation agreements or treaties are signed, in accordance with the established format by the 1986 Vienna Convention the information on:

- time, exact geographical co-ordinates of the NPP and nature of the accident;
- possible or determined cause of the accident as well as the forecasted development of the accident, related to possible transboundary radioactive contamination;
- characteristic features of radioactive contaminants, including their nature, possible physical-chemical form, quantity, composition and effective emission height;
- current and forecasted hydromeorological conditions in order to predict transboundary radioactive contamination;
- results of gamma environmental monitoring, in relation to transboundary radioactive contamination;
- on-going and planned radiation protection measures beyond the area of the sanitary protection zone;
- expected changes in emissions of radioactive substances over time.

In case of any change of the emergency situation, these data are updated, corrected and also provided to the IAEA and neighbouring states directly or through the IAEA and to the countries, with which bilateral or multilateral co-operation agreements or treaties are signed.

As Lithuania has joined the European Union, currently national regulations are taking into account the EU system on urgent exchange of information on radiation (ECURIE).

1.2. Discussions on Future Siting and Risk Zoning

In fact, in the context of some severe external events, the assumption of continued availability of NPP infrastructure required to administer emergency measures (for example roads and bridges) may not be valid. Under such situation, it is more effective to enhance the quality of the other levels of defence in depth. There is therefore, a need to define the scope of off-site emergency planning activities for advanced reactors, consistent with the ability of these reactor designs to meet enhanced safety objectives.

In some cases, such as the presence of a nearby airport, consideration of the hazards may change risk zoning or eliminate a site from further consideration for an NPP, but most external hazards are either screened out from the necessity of being considered further or are taken account of in plant design and siting. Siting and risk zoning is a matter for:

- The uncertainties of risk measures and influence to the public perception;
- Economic consideration (where power is needed, the availability of existing grid);
- Social and political factors;
- Topography affecting the dispersion of radio-nuclides through the atmosphere, rivers and ground-water;
- Political and safety consideration;
- Demographic characteristics;
- Hazards (natural and man made).

Some IAEA member states only address the risk to an individual member of the public, others have requirements to consider the potential aggregated effects to the population as a whole – societal risk.

Off-site emergency measures are still seen as part of the Defence in Depth approach, which is mainly understood in deterministic sense, but to take full advantage of new reactor designs it should also include a more probabilistic approach performing risk, sensitivity and uncertainty analysis. The full benefit of innovative NPP requires the ability to licence without the need of an off-site Emergency Planning Zone.In general, the desirability or possibility of reducing or eliminating emergency response plans for accidents depends not only on the reactor type but also on a number of complex and intertwined factors including technical, societal, economical and cultural. The subject cannot be coupled directly and solely to the requirements for the external events but requires a separate consideration. Under the same subject also the risk-informed decision making related to the design basis accidents and severe accidents are considered with the intent of moving away from postulated risk zones and towards mechanistically calculated risk zones. Without such a change, related procedures and criteria, the issue of the emergency response plans cannot be resolved. In particular, in order to deal with external events and apply the risk-informed approach for plant design and siting, it is desirable to couple the PRA with techniques of civil engineering.

1.3. Further Work for Enhanced Licensing

The ultimate objective for advanced NPPs is to establish an enhanced approach to licensing, reflecting improved safety characteristics of advanced reactors, that is expected to justify and enable revised (reduced or eliminated) emergency planning requirements, while providing at least the same level of protection to the public as the current regulations. Ideally, the emergency planning zone would coincide with (or be contained within) the site boundary, thus, there would be no need for off-site evacuation planning, and the NPP would become, relative to the general population, the same type of facility as any other industrial enterprise.

In order to contribute toward achieving this ultimate objective by addressing some of the relevant issues there is a need to consider the following research tasks:

- Critically evaluate current regulations to identify what changes are necessary to enable advanced licensing.
- Identify criteria based on technical, quantifiable parameters that may be used in support of the objective.
- Identify approach, based on a combination of deterministic, probabilistic, and risk management, that will enable assessment of advanced plants based on their key design operational and safety characteristics with respect to adequate emergency planning requirements.
- Prepare site-specific representative data (e.g., demography, meteorological and etc.).
- Perform probabilistic analyses needed to support this approach.
- Perform deterministic / dose evaluation analyses needed to support this approach.
- Perform a detailed evaluation of the representative reactor utilizing the combined approach.
- Identify, discuss and quantify the benefits attainable through the implementation of this objective, i.e., licensing with reduced emergency planning requirements.

In order to perform these tasks with the ultimate goal of developing a technology-independent approach, the design of IRIS is used as a testbed. IRIS is representative of innovative reactors, and because it is a LWR, its possible sequences and its behaviour under accident conditions is much better understood and predictable than that of some more distant new technologies. Moreover, it has the necessary prerequisite, excellent safety, due to its Safety-by-Design™ approach.

The further work is within the scope of activities defined within the IAEA CRP on Small Reactors with no or infrequent on-site refueling. Specifically, it is relevant to "Definition of the scope of requirements and broader specifications" with respect to its ultimate objective (revised evacuation requirements), and to "Identification of requirements and broader specifications for NPPs for selected representative regions" considering specific impact on countries with colder climate and increased interest for district heating co-generation.

Within this framework the information gathered from the PRA (both internal and external events) will be used to provide a basis for the redefinition of the EPZ defining criteria. This approach consists of coupling the PRA results with deterministic dose evaluations associated to each relevant PRA sequence considered, and thus achieving a technically sound bases for the definition of a plant specific EPZ. In this approach the two basic components of risk (i.e. probability of occurrence and consequences of a given accident) are therefore explicitly combined. The EPZ radius can then be defined as the distance from the plant such that the probability of exceeding the dose limit triggering the actuation of emergency procedure is equal to a specified threshold value. To identify this threshold value, detailed analysis of existing installations should be performed to infer the risk associated with the current EPZ definition.

It must be noticed that the use of existing regulations and installations as the basis for this redefinition will not in any way impact the high degree of conservativism inherent in current regulations. Moreover, the remapping process makes this methodology partially independent from the uncertainties still affecting probabilistic techniques. Notwithstanding these considerations, it is still expected that applying this methodology to advanced plant designs with improved safety features will allow significant reductions in the emergency planning requirements, and specifically the size of the EPZ. In particular, in the case of IRIS it is expected that taking full credit of the Safety-by-Design™ approach of the IRIS reactor will allow a dramatic reduction in the EPZ requirement, while still maintaining a level of protection to the public fully consistent with existing regulations.

1.4. Demography and Related Zones

Population Evolution

Visaginas is part of the Ignalina district. The construction of the nuclear power plant made a big impact on the demography in this district. In 1979 the total population of the Ignalina district was 37,800, and then in 1989 it rose to 59,700, while the population in the country-side decreased from 21,600 to 18,200 [1].

In 1979 the natural population increase rate was 4.8 people per 1000 (the birth and the death rate were 16.1 and 11.3 per 1000, respectively) and in 1989 it was 3.8 people per 1000 (the birth and death rate was 13.5 and 9.7 per 1000, respectively).

The main cause of the increase of population in the Ignalina district was migration to Visaginas. This also led to a significant shift in the nationality of the population of the Ignalina district. In 1979 the percentage of Russians and Russian speakers was about 26 % in 1989 it had increased to about 53 %. This immigration was concentrated in the city of Visaginas which consisted of about 92 % Russians and Russian speakers [1].

Current Population

The distribution of population is important for nuclear activities, as potential radiological impacts may affect wide areas. The nearest major cities to the plant are Vilnius with about 553,000 inhabitants, and Daugavpils in Latvia with 126,000 inhabitants. The city of Visaginas is with about 28,800 inhabitants and residence of the Ignalina nuclear power plant personnel (see following Figure).

Figure 1. Location of the Ignalina NPP (local scale) in the INPP Region

Ignalina NPP region includes the territories of Visaginas, Ignalina and Zarasai municipalities (see map on above Figure). The region under consideration forms a part of Utena County. This is the territory within the observation zone of Ignalina Nuclear Power Plant (beginning of 2004):

• the municipality of Visaginas – 59 square kilometres, 28.8 thousand inhabitants;

• the Ignalina district – 1 496 square kilometres, 22.0 thousand inhabitants;

• the Zarasai district – 1 334 square kilometres, 22.0 thousand inhabitants.

As many as 2.3 per cent of the population of the country lives in this region.

The main information about the population distribution in the region of 30 km is presented in the following Table and Figure [2].

Table 2. Population Distribution (thousands)

Direction of segment / Radius of circle	N	NE	E	SE	S	SW	W	NW	Amount of inhabitants in the ring	Amount of inhabitants in the circle
30 km	38.9	0.8	8.8	1.4	1.8	2.4	2.3	0.9	57,3	135.9
25 km	1.4	1.1	2.5	2.6	4.7	1.6	1.4	8.7	24.0	78.6
20 km	0.5	0.4	1.4	1.3	1.3	2.9	0.9	0.7	9.4	54.6
15 km	0.6	0.8	1.0	0.9	0.9	1.3	0.4	1.0	6.9	45.2
10 km	0.5	0.6	0.7	0.5	1.0	0.5	34.0	0.3	38.1	38.3
5 km	-	-	-	-	0.1	-	-	0.1	0.2	0.2
3 km	-	-	-	-	-	-	-	-	-	-
Amount of inhabitants in the segment	41.9	3.7	14.4	6.7	9.8	8.7	39	11.7	Total 135.9	

About 38 thousands of inhabitants of Daugavpils (Latvia) have to be included into the 30 km radius zone because 30% of territory of Daugavpils stretches at a distance from 27 to 30 km from INPP. Within the 30 km radius the density of population is about 48 people/km2. This is lower than the nominal density of population of 56.7 people/km2 in Lithuania. In fact, population density in the INPP region is one of the lowest in Lithuania.

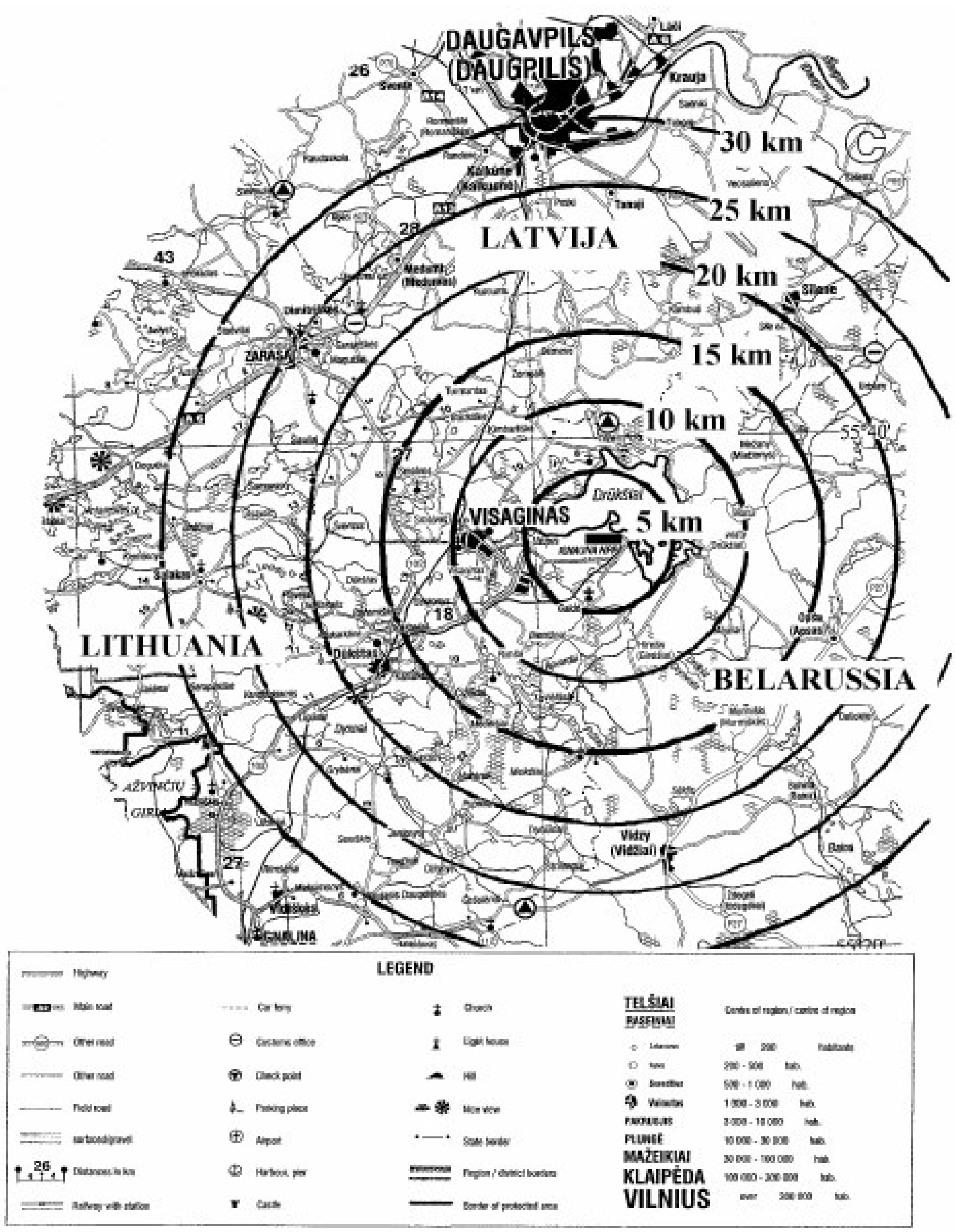


Figure 2. Population Distribution in 5, 10, 15, 20, 25 and 30 km Zones [2]

Apart the city of Visaginas itself, made essentially of multi-level buildings, there are some small villages in the vicinity of the plant, such as Mačyonis and Vyšniava.

Within the sanitary protected zone (established for emergency planning purposes, R = 3 km) there are neither farmsteads nor inhabitants.

2. ECONOMIC IMPACT OF NPP-BASED DISTRICT HEATING

A performed study of the economic impact of revised licensing requirements on district heating is based on economic evaluation of the nuclear district heating cogeneration option.

Due to climate conditions, district heating presents a notable fraction of energy consumption in winter months, and infrastructure for its use is already in place in population centers in Lithuania. Heat energy cannot be transported in a long distance because of the big losses in the heat supply network. So it is necessary to have heat energy supply source as close as possible to heat consumers. If IRIS could be built near the large cities (without EPZ) where a big heat demand is, it could be used not only for electricity generation, but also for heat supply for residential and industrial consumers. This will allow not only to reduce energy prices but also to decrease fossil fuel consumption and emissions into atmosphere. So there is a high necessity of eliminating or reducing emergency planning for the future small and medium nuclear ractors.

2.1. Primary Data and Modelling Tool

2.1.1 Primary Data

Total installed capacity of the Lithuanian power plants is about 4900 MW, including one unit of Ignalina Nuclear Power Plant (NPP) with 1500 MW installed capacity and the Lithuanian Thermal Power Plant (Lithuanian TPP) with 1800 MW. Installed capacity in Combined Heat and Power plants (CHP) accounts for about 780 MW, Kruonis Hydro Pumped Storage Power Plant for 800 MW, hydro power plants for 120 MW, etc. Maximal domestic electricity demand in 2003 was 2015 MW. There are three large CHP plants in Lithuania (Vilnius, Kaunas and Mazeikiai). There are also several small public CHPs and industrial cogeneration plants. Mazeikiai CHP is oil-fired and all other plants are dual fuel (oil or gas). Lithuania also has a large district heating system. Lithuania has a well-developed electricity network and strong connections with Latvia and Belarus. However, it has no direct connection with its southern neighbour – Poland.

Until 2005, Ignalina NPP was generating up to 85% of total electricity in Lithuania. However, the first unit of the Ignalina NPP was closed at the end of 2004 and the second one will be closed before 2010. This will lead to very significant changes in the Lithuanian power system as well as in the whole energy sector. The results of various studies concerning the future structure of power plants in Lithuanian energy system have showed that looking from the economical point of view Ignalina NPP should be replaced by a modernised Lithuanian power plant or new combined cycle condensing units together with the existing and new CHP units [6, 7, 19]. In the future new cogeneration units are likely to be the best alternative for electricity and heat generation in Lithuania if energy demand grows. The construction of new nuclear power plant at Ignalina site is also one of the options, but because of its big unit size and investments (1000 MW and overnight investment cost at least 1500 $/kW) new nuclear unit in the middle term time period won't be competitive in Lithuanian electricity market.

IRIS could be a rather attractive option of nuclear technology for Lithuania because of its medium size (335 MWe) units compatible with predicted Lithuanian needs on new nuclear power deployment by 2015. Nuclear power units smaller than currently available reactors and flexible arrangement (multiples of single or twin-units) are much more compatible with Lithuanian needs for slow increase in generating capacity, enabling economic base-load use of nuclear power plant. Its predicted total overnight cost [13] is in the range of investment cost at which new nuclear power plant may become competitive in Lithuanian power system. The levellized cost of electricity production is in the range of 2.0 - 3.1 c/kWh and competitive with other possible alternatives [9], which means that IRIS is a plausible electricity generation option after decommissioning of the second unit of the Ignalina NPP. The comparatively small size of each module reduces the investment needed for a new unit and improves cash flow. Continued operation of nuclear technology will also diversify Lithuanian primary energy balance, reduce dependency on natural gas and fossil fuel price fluctuation. In addition, it will help to benefit from emission trading or even to solve future problems related to environmental obligations [9].

The IRIS offers a significant reduction and simplification of the passive safety systems, which not only improves safety but simultaneously reduces the overall cost. Moreover, it supports licensing the power plant without the need for off-site emergency response planning. This would allow IRIS to be treated as any other industrial facility, located closer to population centres. The excellent safety characteristics of IRIS allow a larger choice of sites and avoiding the expenses of physically preparing the site and conducting planning for emergency response. This allows better implementation of cogeneration option and reduction of transmission costs.

Seeking to have consistent modelling of the energy sector development in this work, final electricity and heat demand was used as input information for the model. The future projections of net electricity production by scenarios are presented in Figure 3. The growth rate of heat demand for different counties is presented in Table 3.

The projections of prices on main imported fuels in Lithuania are presented in Table 4. Typically, energy prices are important drivers of total energy demand and supply. Average end-user prices on fuels and energy are derived from fuel prices on wholesale markets. In general, the assumed trend of oil and gas prices should reflect the trend of crude oil price on the world market. These fuel price projections also were used in other studies, which were analysing future development scenarios of the Lithuania energy system.

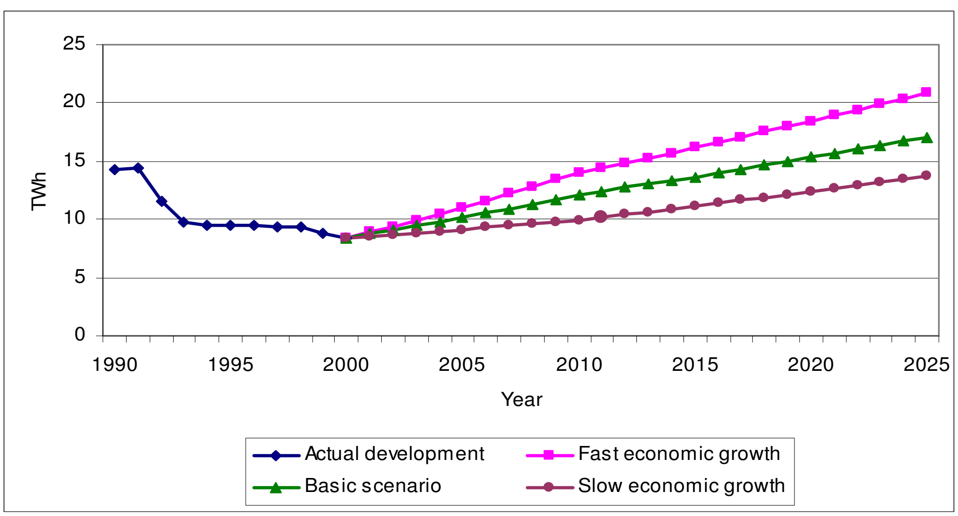


Figure 3. Electricity Demand by Scenarios [7]

Table 3. The growth rate of heat demand, % [19]

Scenario	County	2005	2010	2015	2020	2025
Basic scenario	Kaunas	2.5	2.5	1.5	1.5	1.5
	Vilnius	2.5	2.5	1.6	1.6	1.5
	Other	2.1	2.1	1.3	1.3	1.3
Slow economic growth	Kaunas	2	1.8	0.62	0.62	0.6
	Vilnius	2.1	1.9	0.62	0.62	0.6
	Other	1.4	1.3	0.62	0.62	0.6
Fast economic growth	Kaunas	3.8	3.2	1.7	1.5	1.4
	Vilnius	3.7	3.1	1.5	1.4	1.3
	Other	3.5	3	1.3	1.2	1.1

Table 4. Fuel prices and its forecast, US$/toe [7]

Fuel	Fuel price scenario	2005	2010	2015	2020	2025	2035
Crude oil	Low	220	221	222	223	224	226
	High	280	330	333	334	336	338
	Extra high	330	330	333	334	336	338
Natural gas	Low	104	125	138	147	158	158
	High	132	155	171	182	196	196
	Extra high	155	188	207	221	237	237
Heavy Fuel Oil (Low sulphur)	Low	146	150	157	160	161	161
	High	186	218	228	233	235	235
	Extra high	218	225	235	240	242	242
Coal	Low	69	69	69	70	72	72
	High	88	103	104	105	107	107
	Extra high	103	103	104	105	107	107
Orimulsion	Low	92	92	92	92	92	92
	High	117	138	138	138	138	138
	Extra high	138	138	138	138	138	138

2.1.2 The Modelling Tool

In order to reach the study objective the MESSAGE modelling tool was used for modelling of the future energy system development in Lithuania. MESSAGE is designed to formulate and evaluate the alternative energy supply strategies consonant with user-defined constraints on new investment limits, market penetration rates for new technologies, fuel availability and trade, environmental emissions, etc. The underlying principle of the tool is the optimisation of an objective function under a set of constrains [17]. It was originally developed at the International Institute for Applied Systems Analysis. The International Atomic Energy Agency acquired the latest version of the MESSAGE and added a user-interface to facilitate its applications.

This modelling tool is extremely flexible and can also be used to analyse energy/electricity markets and climate change issues. The representation of the energy system used in MESSAGE is based on a network concept. The activities and relationships of an energy system are described as an oriented graph, depicting the energy chain starting from extraction or supply of primary energy, passing through several energy conversion processes (e.g. electricity generation, transmission and distribution) in order to satisfy the demand for final energy.

Each sub-system of the created model contains a set of existing and new technologies. The objective of model application is determination of an optimal allocation of these technologies and the associated energy resources to satisfy the projected final energy demand. The mathematical method used in the MESSAGE model is linear programming, which means that all technical and economic relations describing the energy system are expressed in terms of linear functions. The optimisation criterion or objective function of the programme is the minimization of the present value of the cumulated energy system costs in the analysing period. However, the definition of other objective functions, such as the minimization of air pollution or of energy imports is possible, either separately or by using a multicriteria approach.

The technologies are represented and aggregated in the model in such a way that the real technological energy supply structure of a country or region is represented in a reasonable way. The technologies are represented by a set of parameters in the model database, which is transformed into the model's system of equations by a matrix generator programme. Such parameters are e.g. prices of primary energy curriers, investment, fixed and variable costs, of various technologies, energy conversion efficiencies, existing capacities, availability factors, emission factors and others.

The application of the model based on MESSAGE tool results in a least-cost inter-temporal mix of primary energy, energy conversion and emission control technologies for each scenario. Scenarios may represent different hypotheses on important parameters, like the future fuel price, the market penetration of new technologies, political decision on development of one or another type of technology, etc., in order to take into account uncertainties in the future. By analysing the results, "what if?" statements on the future energy supply structure can be made, and different strategies of utilization of various primary energy sources can be compared with respect to their emission reduction efficiencies and their impact on structure and economy of the energy system.

2.2. Mathematical model

2.2.1 Model for the Analysis of Energy Sector

This model was created on the basis of the above-described MESSAGE modelling tool. The mathematical model prepared for the analysis of development of the Lithuanian energy system represents the whole energy system of the country, including all processes from the primary energy extraction or import to the supply of final energy. However, the main attention was paid to heat and electricity supply sectors while other sectors were represented in a simplified way. Power and heat supply systems are very interdependent. Both systems are being connected by CHP plants. Therefore, the future development of these sectors cannot be analysed separately. The model is adjusted to specific country conditions in order to represent correctly peculiarities of Lithuanian energy system.

Shortly the created model can be characterized by the following properties:

- It is an energy supply model, representing the energy conversion and utilization processes of the energy system;
- It is an optimisation model which from the set of existing and possible new technologies selects the optimal, in terms of selected criterion, mix of technologies able to cover given country demand for various energy forms during the whole study period;
- A techno-economic or engineering approach is applied, i.e. the model represents the energy systems by its technological structure, aiming at the optimisation of this structure, generally with respect to energy system costs;

- It is used for the development of medium-term strategies;
- It takes into account demand variations of various final energy forms during day, week and seasons, as well as different technological and political constrains of energy supply;
- It is an energy and environmental model, enabling the user to carry out the integrated analysis of the energy sector development and its environmental impacts;

The created model consists of 12 different modules, which are connected by technologies representing energy transmission or distribution (Figure 4). The following modules (“Vilnius”, “Kaunas”, “Alytus”, “Taurage”, “Utena”, “Panevezys”, “Siauliai”, “Klaipeda”, “Telsiai” and “Marijampole”) represent heat supply systems in 10 counties of Lithuania together with modules “Fuel” and “Electricity”.

Heat energy cannot be transported in a long distance so heat supply sector consists of many district-heating systems. Therefore, district heating systems have to be aggregated taking into account technical and economical aspects and other selected criterions. So heat supply systems were aggregated according to its dependence to a particular county of Lithuania. The existing CHP power plants and boiler-houses, networks of district heating, as well as other present infrastructure of heat and electricity supply systems, are modelled in every module. The option of modernization of existing CHP power plants and boiler-houses is foreseen in the model. Also there is a big list of new heat energy generation technologies, which can replace the existing ones in the future. These future energy generation technologies are: new renewable boiler houses, new gas boiler houses, new gas or renewable CHP plants, new small CHP plants, new decentralized heating systems based on individual gas fired boilers, construction of new IRIS nuclear power plant(s) with cogeneration option in some of the counties (at least Vilnius and Kaunas). Electricity produced by cogeneration plants is supplied to national transmission or distribution networks, which are modelled in “Electricity” module. In parallel to energy generation technologies, emission abatement technologies are modelled.

Module “Electricity” represents the electricity supply system. In order to find a future structure of Lithuanian energy system, together with existing power plants a set of new possible technological options was analysed: modernization of Lithuanian TPP, including flue gas desulphurisation measures; construction of new Combined Cycle Gas Turbine (CCGT) units at different sites; construction of wind power plants, etc.

System of fuel supply is represented in “Fuel” module. It models import, preparation, transportation and distribution of gas, oil, orimulsion and other fuels. Variable cost of technologies representing the import of various fuels includes fuel prices in the world market and transportation cost till Lithuanian border.

2.2.2 Options for Future Energy Supply System

Lithuanian TPP consists of four 150 MW and four 300 MW units. The units may be operated at full load until 2025-2030. Utilization of those units at full load would likely start only after shut down of the second unit of the Ignalina NPP. However, in order to prepare this power plant for reliable operation after 2010 units should undergo minor modernization.

Vilnius CHP-3 total installed electric capacity is 384 MW, it has two turbines with thermal capacity 2x302 MW. This power plant can fire both natural gas and heavy fuel oil. The fuel type is chosen depending on the fuel prices. In order to comply with environmental standards on emissions installation of low NO_x burners will be required.

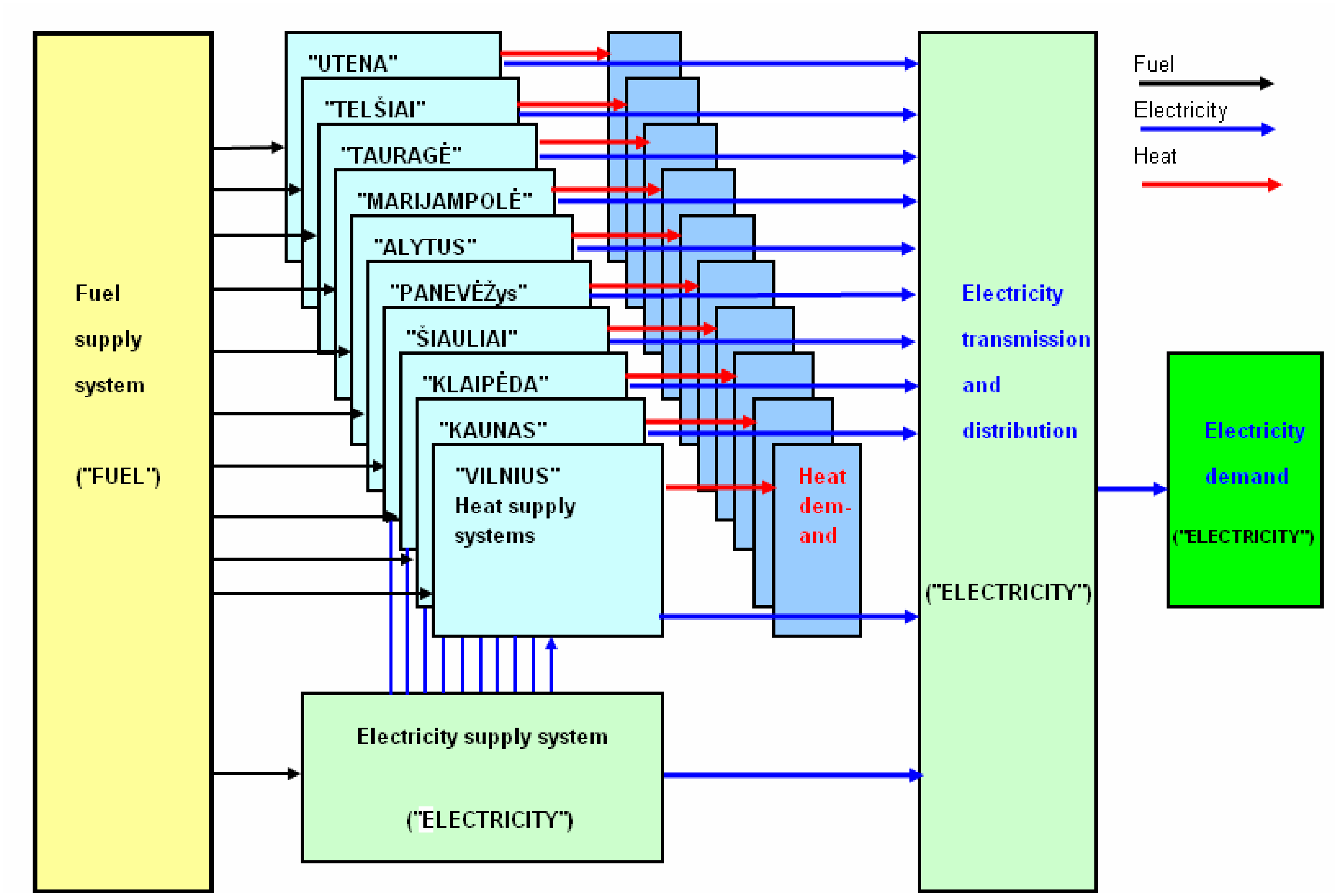


Figure 4. Structure of the model

Kaunas CHP total installed electric capacity is 170 MW, thermal capacity of Kaunas CHP turbines is 186 MW and 203 MW. In addition, Kaunas CHP has 4x116 MW and 209 MW of water heating boilers and 255 MW of heat exchangers that can convert high potential (pressure and temperature) heat from steam boilers into low potential heat that can be delivered to residential consumers. Similarly to Vilnius CHP-3, Kaunas CHP will require some modernization.

Mazeikiai CHP total installed electric capacity is 194 MW, thermal capacity of Mazeikiai CHP turbines is 2x215 MW. This power plant can fire only heavy fuel oil.

Kaunas hydro power plant and Kruonis hydro pumped storage plant. Total capacity of Kaunas hydro power plant is 100 MW. Annual electricity production fluctuates between 280 and 440 GWh depending on water flow. The Kruonis HPSPP was built in 1992-1998 and comprises four units of 200 MW each. The plant serves peak and semi-peak loads of the Lithuanian power.

IRIS. New medium sized advanced light water cooled modular reactor with cogeneration option (IRIS) could be constructed at the different sites of Lithuania, for example Vilnius, Kaunas or other places where there is a demand for heat. The modular IRIS (with each module 335 MWe) is an ideal size for small countries like Lithuania, as it allows to easily introducing single modules in regions only requiring a few hundred MWs, or a moderate amount of power on limited electric grids. IRIS can be also deployed in multiple modules successively at time intervals in areas requiring a larger amount of power increasing with time. It is assumed that IRIS could start its operation in 2015. IRIS reactor also could be built only for electricity generation (if assuming current EPZ). In this case the existing site of Ignalina NPP (after its decommissioning) could be used in order to utilize exisistg infrastructure and to lower construction cost.

New CHP plants. In addition to the above mentioned existing power plants it will be possible to install new CHP plants for supply of electricity and heat in existing district heating systems in Lithuania.

New Combined cycle gas turbine power plants. New CCGT plant can be built at the site of Ignalina NPP, after its decommissioning to utilize existing site, infrastructure and qualified personal. Similarly, existing space on the site of the Lithuanian TPP can be used for construction of new CCGT units. This can be done in addition to the existing capacities or instead of rehabilitation of existing units. New CCGT plants also can be constructed at new sites in Lithuania. This, however, will require higher investment costs and extension of gas network.

New wind power plants. Because Lithuania does not have sufficient primary energy resources, electricity production based on renewable energy sources could be very attractive. One of possible ways to utilize renewable energy is construction of wind power plants. However, total installed capacity was constrained by 200 MW taking into account limited number of available sites with comparatively high wind speed.

Conversion of existing boiler-houses into CHP. Existing boiler-houses can be converted into CHP.

Reserve capacity. 10% of installed capacity from each power plant was assumed to be used for reserve capacity in order to satisfy necessary requirements in electricity system. Major part of capacity of Kruonis hydro pumped storage power plant was also allocated for reserve.

Main parameters of technologies producing electricity and heat are summarized in Table 3.

Introduction of IRIS into Vilnius and Kaunas district heating systems is analyzed, therefore a few facts about district heating systems of two biggest cities in Lithuania is presented.

Vilnius district heating (DH) system supply heat for 80% building in the city. 73 % of supplied heat is used for space heating. The heat price for final users was 2.9 Euro ct/kWh in 2005. The lenght of district heating pipelines in Vilnius is ~557 km and losess was ~18%.

To the **Kaunas district heating** system is connected 3740 buildings. The heat price was 3,4 Euro ct/kWh in 2005. The length of DH networks is 417 km and a loss in pipelines was 22%.

New district heating pipelines. They are needed to connect IRIS units to existing district heating systems. In the modern district heating systems pre-isulated pipes with efficient insulation material of polyurethane is used to decrease a heat loss in the heat transmission from production to final consumer. In the calculations it was assumed that heat losses in the heat transmission pipes which lenght is until 15 km - 1%, 15-25km – 2% and 25-30 km – 3%. Ussualy pipelines are constructed underground and installation is expensive. The investment amount to new DH pipelines depends on needed capacity (throughput) and length of pipe. In the analysis the investment cost to DH network is estimated 10,8 $/kW/km. Ussualy large energy producers are constructed on the edge of the city (as in the case of Vilnius and Kaunas DH systems). Therefore, it is assumed that the connection point of new large scale heat producer to district heating network is near existing CHP and new pipeline is 0,5 km. In the scenario with different EPZ, the new DH pipeline is constructed to connect existing CHP and new IRIS which is constructed contrariwise to the city centre.

Table 5. Technologies representing System of Electricity and Heat Generation

Plant name	First year of operation	Plant factor	Operation time	Econ.plant life	Construction time*	Investment cost**
	Year	Fraction	Fraction	Year	Year	US$/kW
IRIS (single module)	2015	0.95	0.98	40	3	1410
New nuclear PP	2010	0.9	0.9	30	4	1500+
New CCGT at Ignalina	2007	0.9	0.9	25	2	400
New CCGT at Elektrenai	2007	0.9	0.9	25	2	400
New CCGT	2007	0.9	0.9	25	3	500
New CHP	2006	0.9	0.9	30	3	800
New small CHP	2006	0.9	0.9	15	1	500
New CHP on renewables	2006	0.9	0.9	30	2	1000
New Gas boilers	2006	0.9	0.9	20	1	100
New Wind PP	2005	0.3	1	30	1	1050
Existing hydro power plants		0.9	0.9	30	1	123
Ignalina NPP		0.9	0.76			
Lithuanian 300MW units		0.9	0.9	20	1	36
Lithuanian 150MW units		0.9	0.75	20		0
Vilnius CHP		0.9	0.82	20	1	40
Kaunas CHP		0.9	0.82	20	1	86
Mazeikiai CHP		0.9	0.82	20	1	71
Klaipeda CHP		0.9	0.72	5		0
Oil/gas boilers in cities		0.9	0.8	30	1	25
Biomass boilers in cities		0.9	0.8	30	1	30

*Construction time for existing power plants represents time necessary for their modernization.

**Investment cost for existing plants represent investment cost for their modernisation.

2.3. Results of Economic Study

This section presents analysis results of the Lithuanian energy system development (with IRIS construction option). Scenarios defined have been optimized using the above-described MESSAGE model in order to determine the optimal development path for the energy sector of Lithuania until year 2025.

2.3.1 Scenarios analyzed

Scenarios analyzed are described in the Table 6.

Table 6. Description of scenarios

No	Scenario name	Description
1	No IRIS	Base scenario: construction of IRIS NPP is not allowed
2	IRIS Cogeneration	Construction of IRIS NPP (with cogeneration option) is allowed in Vilnius and Kaunas cities. No additional heat supply networks required. Construction of IRIS units only for electricity production is also allowed in other locations.
3	IRIS with EPZ	Construction of IRIS NPP (with cogeneration option) is allowed in Vilnius and Kaunas cities. Additional heat supply network must be constructed. The EPZ is assumed to be 5-30 km. Construction of IRIS units only for electricity production is also allowed in other locations.
4	IRIS electricity only	Construction of IRIS units used only for electricity generation is allowed (no cogeneration option).

All scenarios described there are calculated assuming low fuel prices (Table 4). The higher fossil fuel prices make IRIS reactor even more attractive option for electricity and heat generation. The possible price increase of nuclear fuel used for IRIS units is not estimated in this study.

2.3.2 Objective function

Differences in the total objective function of the Lithuanian energy system operation and development among scenarios mentioned above could be seen in Fig. 3 where value of objective function is presented for all scenarios analysed. Objective function represents total discounted cost of the Lithuanian energy system operation and development in the time period from 2000 until 2025.

Optimisation of the Lithuanian energy sector has shown that base scenario (No IRIS) has caused higher total discounted cost of the Lithuanian energy system operation and development if compared to the other scenarios (Figure 5). Therefore, it means what construction of IRIS units would be an economically attractive option. The scenario with IRIS cogeneration units in Vilnius and Kaunas cities caused lowest total discounted cost. The construction of additional heat supply pipes increases costs, but they still remain below the value when IRIS units are used only for electricity generation.

The results of the calculated scenarios are described below.

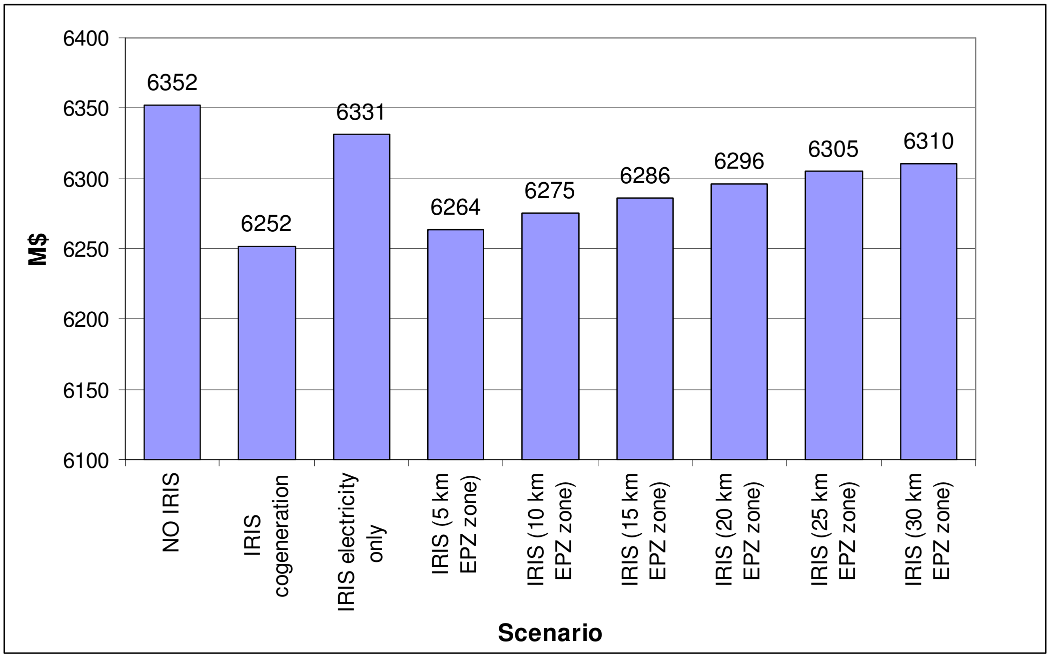


Figure 5. Discounted cost of energy system operation and development in 2000-2025

2.3.3 Base scenario

Electricity production in Lithuania in the case of "No IRIS" scenario (base scenario) is presented in Fig. 4. Before closure of the second unit of the Ignalina NPP the electricity production from nuclear fuel is dominant in Lithuania. Share of electricity produced at Ignalina NPP in 2005-2010 makes 61-69 % while before 2005 its production was even higher. Combined heat and electricity production units produce 9-19 % from total electricity generation in period 2005-2010. Electricity generation after closure of the Ignalina NPP becomes rather diversified. Modernised Lithuanian TPP in this case will take dominant position after 2010, and will generate up to 44% of total electricity. Orimulsion as the main fuel will be used at this power plant. Existing and new CHP power plants, mainly using natural gas as a fuel, will cover the biggest part of Lithuanian electricity demand. Electricity production of all CHPs in 2010 is valued at 6.8 TWh what makes 54.8 % of total electricity and in 2025 reaches 8.3 TWh or 46.9 %. It is necessary to note that electricity production at CHP after closure of the Ignalina NPP unit 2 has the highest increase among all technologies analyzed. CHP plants as energy source is the most attractive technology after closure of nuclear power plant, but its expansion is limited by heat demand in heat markets.

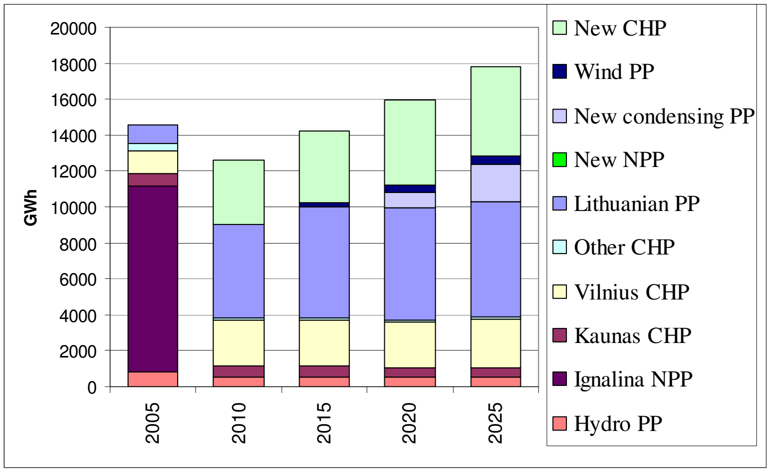


Figure 6. Dynamics of electricity production in the case of “No IRIS” scenario

According to the assumed energy demand projections, total final heat demand in Lithuania is growing from 10.1 TWh in 2005 up to 12.9 TWh in 2025. Heat production is much higher because of losses at heat distribution networks. Total heat output from all production sources in the same time period is increasing from 13.44 TWh until 17.36 TWh. Dynamics of heat production by technologies is shown in Figure 7. At the moment the biggest part of total heat is produced at heat only boilers (HOB) and CHP power plants in biggest cities of Lithuania. In the future fast penetration of CHP in heat market is possible, so new CHP power plants using natural gas and renewable energy sources should replace existing HOB gradually. In addition, decentralized heating could take noticeable part of the heat market in year 2025. Natural gas is the main fuel for heat production in Lithuania. Heat generated in Vilnius and Kaunas cities makes 54-56% from total heat produced in Lithuania, accordingly these two cities were chosen as suitable for the construction of IRIS units.

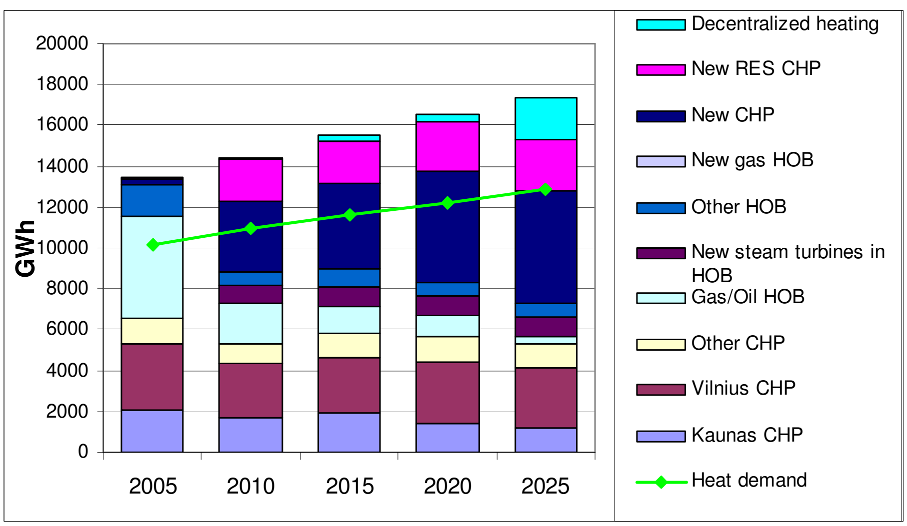


Figure 7. Heat production by technologies in Lithuania (“No IRIS” scenario)

2.3.4 IRIS main scenario

The results of energy system optimization have showed that building of IRIS reactors for electricity and heat cogeneration in two main cities of Lithuania is economically attractive option. Modernisation and operation of the Lithuanian TPP (used only for electricity generation) in the middle term time period (after closure of Ignalina NPP) will not prevent from deployment of IRIS NPP units. In this scenario three IRIS units operating in cogeneration mode are built. Additional units which could produce only electricity were not constructed. The first units are built in Kaunas and Vilnius cities before year 2015. The second unit in Vilnius city is constructed and started its operation before year 2020. The total capacity of these IRIS units (1005 MW) makes 22.6-26.6% from total installed capacity in Lithuania in the period 2015-2025. Electricity production in Lithuania in the case of IRIS main scenario (base scenario) is presented in Fig. 6.

In this case IRIS units will supply 37% from total electricity production in Lithuania in 2015, 49% in 2020 and 44% in 2025. Annual electricity production of IRIS units in this time period reaches 5.2-7.9 TWh. Because of IRIS generation significant decrease of electricity production at Lithuanian power plant occurs. Its share in 2010 makes 46% while in 2015 already 17.9 % and further decreases to 14% in 2025. If compared to the base scenario electricity production at existing and new CHP power plants also decreased. In base scenario all CHP power plants generated 6.8-8.3 TWh of electricity annually in period 2010 – 2025, and in IRIS scenario these power plants generated 5.5-6.6 TWh of electricity.

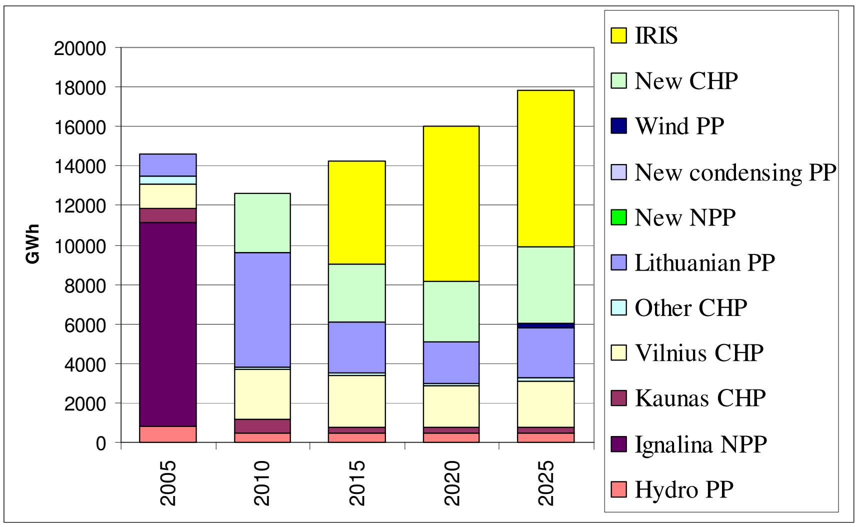


Figure 8. Dynamics of electricity production in the case of “IRIS cogeneration” scenario

Dynamics of total heat production in Lithuania by technologies in “IRIS cogeneration” scenario is shown in Figure 9. In this case, IRIS units in Kaunas and Vilnius will supply 29% from total heat production in Lithuania in 2015, 37% in 2020 and 31% in 2025.

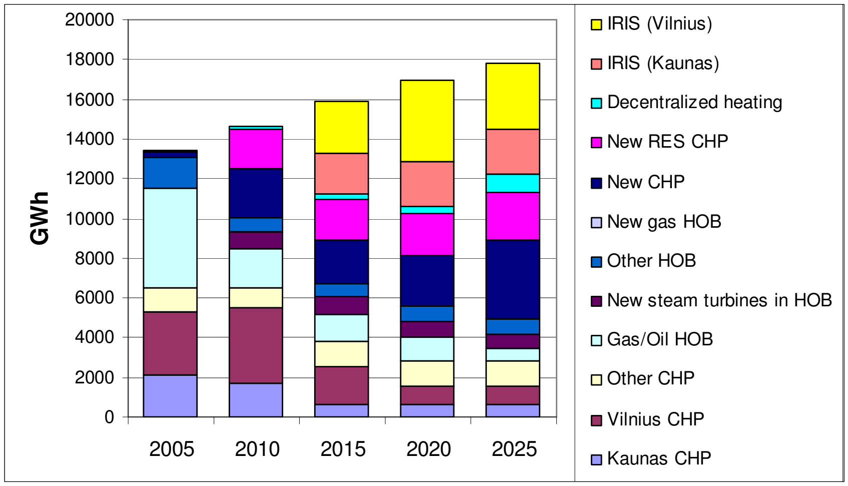
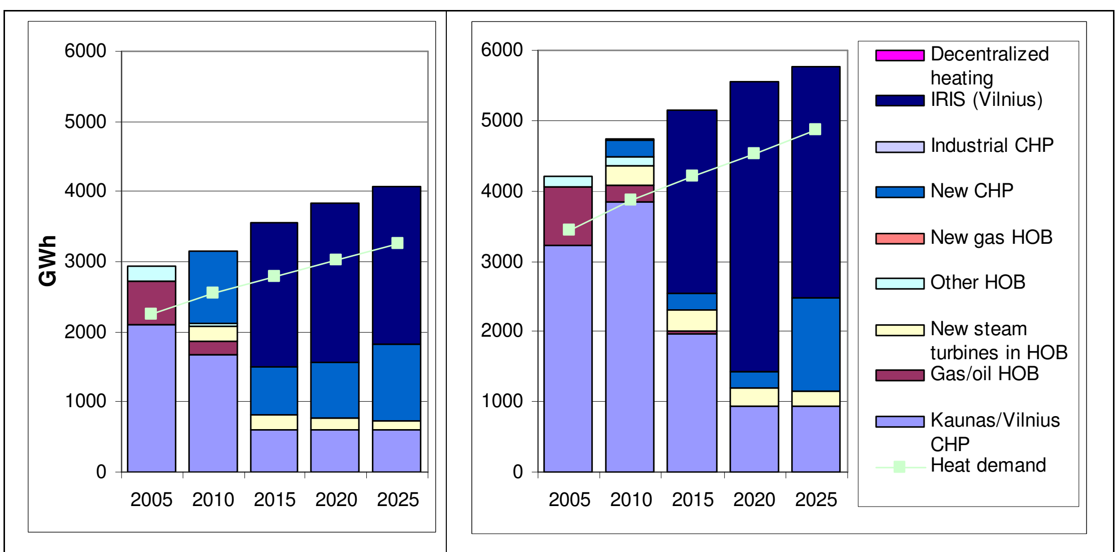


Figure 9. Heat production by technologies in Lithuania ("IRIS cogeneration" scenario)

Heat production at Kaunas and Vilnius cities are shown in Figure 10. Annual heat production of IRIS units in time period 2015-2025 reaches 2.6-4.1 TWh at Vilnius city (it is 51-74% from total heat production) and 2-2.3 TWh at Kaunas city (55-58%). Because of IRIS generation, heat production at Kaunas and Vilnius CHP power plants decreases. Compared to the base scenario heat production at Vilnius CHP decreases 1.4-3.2 times depending on the year analyzed and at Kaunas CHP it decreases 1.9-3.1 times. The similar situation is also with new CHP power plants in these two cities. In the base scenario the electric capacity of new CHP power plants in Vilnius city were 114-150 MW and in Kaunas 76-141 MW. In IRIS main scenario the total installed capacity of new CHP power plants decreases to 8-83 MW in Vilnius city and to 60-75 MW in Kaunas city. So the construction of IRIS units completely changes situation in the heat markets of Kaunas and Vilnius.



a) Kaunas b) Vilnius

Figure 10. Heat production in Kaunas and Vilnius ("IRIS cogenearation" scenario)

The construction of IRIS units introduce significant changes in the countries' fuel balance which is used for the electricity and heat generation. In the base scenario, after the closure of Ignalina NPP in 2009, electricity production from orimulsion becomes the most economically efficient in Lithuania. Natural gas and orimulsion makes up to 90-91% from the total fuel for energy generation. In case orimulsion supply will be restricted by some up to now unknown reasons it could be easily replaced by natural gas or heavy fuel oil. In extreme cases all orimulsion can be substituted by oil or by gas. In the case of IRIS scenario the share of natural gas and orimulsion in the fuel balance will decrease to 44-56 % (Figure 11). So the construction of new nuclear units and diversification of fuel balance could increase security of energy supply in Lithuania.

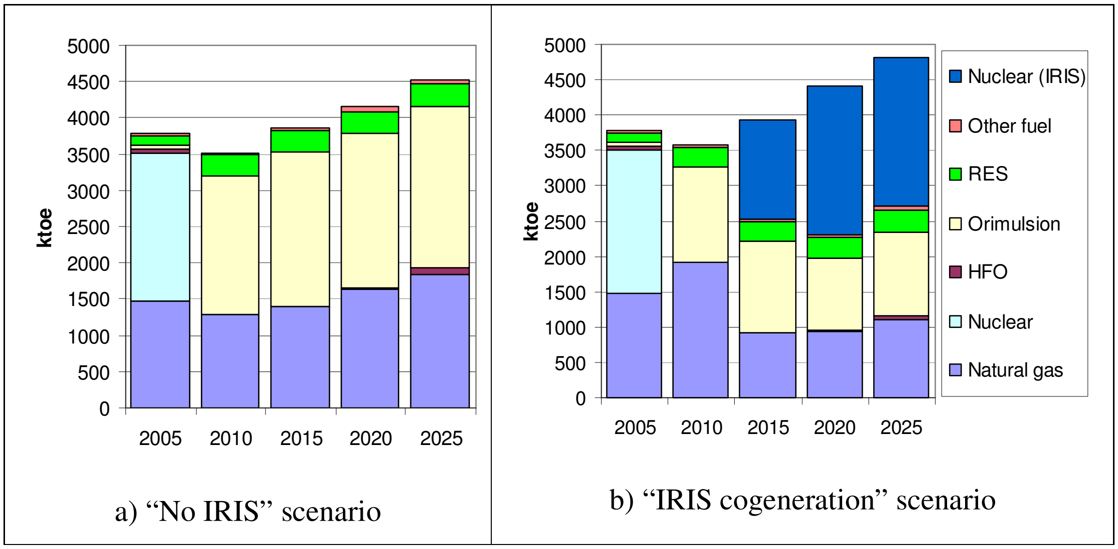


Figure 11. Fuel consumption for electricity and heat generation (two scenarios)

2.3.5 IRIS units with EPZ

This set of scenarios illustrates situation in case IRIS units could not be built near to the heat users and additional heat supply networks must be constructed. Few scenarios were calculated while increasing the EPZ from 5 to 30 kilometres (every 5 km) assuming that this is the length of additional heat supply pipe.

The calculation results of these scenarios are summarized in the Table 7. This table presents main parameters characterising operation of IRIS units and how they vary depending on EPZ (construction of additional heat supply pipe). Only scenarios with significant or interesting changes in structure of generating capacities or energy production were presented in this table. Table 7 presents number and capacity of constructed IRIS units, total investments for construction of additional heat supply network and its installed capacity, electricity generation volumes at IRIS units and its share from total electricity generation in Lithuania and heat generation volumes at IRIS units. The results are compared to the ones of the IRIS cogeneration scenario.

In all scenarios independently on length of heat supply pipes, three IRIS units are constructed with total electrical capacity of 1005 MW. If the zone length is between 0-15 km all three units are with cogeneration option: two units are constructed in Vilnius and one in Kaunas. If zone length is between 15-30 km third unit is constructed only for electricity generation, and in the cogeneration mode operates one unit per city (Kaunas and Vilnius). Mainly this is because of the high investment to the new heat supply pipes. The total investment cost for additional 5 km length pipes is 72.5 M$, for the 15 km length pipes – 142.3 M$, for the 20 km length pipes – 177.9 M$. However if the zone length is increased to the 25 km and more the total investment cost for the construction of pipes is decreasing: it is 157.9 M$ for 25 km pipe and 141 M$ for 30 km. The reason for this is the reduction of the pipe capacity, which is decreasing while the length of the pipe is growing up. This is because longer heat pipe has bigger heat losses. This means that not all heat energy, which could be produced at the IRIS power plant is efficient to supply to the consumers. So, the production of additional heat (for the coldest but relatively short time periods) at other heat supply sources is more economically attractive option. This also explains why one of the IRIS units is constructed only for the electricity generation if the length of pipe is beyond 15 km. The results shows that heat supply pipe capacity in Vilnius city reduces from 485 MW to 179 MW if the length of pipe increases from 15 km to 30 km. The same situation is in the Kaunas city: capacity of pipe reduces from 393MW to 256 MW (Table 7).

Table 7. The main results of IRIS EPZ scenarios

	EPZ (length of heat pipeline), km			
	IRIS cogeneration scenario*	5	15	30
Objective function		6263848	6286201	6310482
Installed units, number (MW)	3 (1005)	3 (1005)	3 (1005)	3 (1005)
Total invest. for heat supply pipes, M$	7.3	72.5	142.3	141.0
Installed capacity of new heat pipes in Vilnius, MW				
2015	485	485	485	173
2020	970	858	485	179
2025	970	858	485	179
Installed capacity of new heat pipes in Kaunas, MW				
2015	485	344	337	215
2020	485	485	393	256
2025	485	485	393	256
Electricity generation				
IRIS with cogeneration, TWh				
2015	5.23	5.25	5.25	5.34
2020	7.87	7.88	5.23	5.3
2025	7.92	7.93	5.24	5.32
IRIS only electricity, TWh				
2015	0	0	0	0
2020	0	0	2.73	2.73
2025	0	0	2.73	2.73
Share from total electricity generation in Lithuania, %				
2015	37	37	37	38
2020	49	49	50	50
2025	44	45	45	45
Heat generation				
IRIS Vilnius, TWh				
2015	2.61	2.61	2.61	1.29
2020	4.1	4.1	2.74	1.57
2025	3.29	3.28	2.53	1.36
Share from total heat gen. in Vilnius, %				
2015	51	51	51	26
2020	74	74	50	29
2025	57	57	44	24
IRIS Kaunas, TWh				
2015	2.05	1.64	1.64	1.16
2020	2.26	2.06	1.97	1.55
2025	2.25	2.06	1.89	1.47
Share from total heat generation in Kaunas, %				
2015	58	47	47	34
2020	59	55	52	42
2025	55	51	47	38

* It was assumed 0.5 km additional heat supply pipe.

As it already has been mentioned the heat produced and supplied to the final users depends on the length of the pipe. If the pipe length is up to 5 km heat production in Vilnius city is 2.61 TWh in 2015, 4.1 TWh in 2020 and 3.28 TWh in 2025. The share of IRIS produced heat in the total heat production in Vilnius is 50-74% depending on the year. If the length of pipe increases, the heat production is starting to decrease (Figure 12). For example, in year 2025 heat generation in Vilnius city is 2.53 TWh (if pipe length is 15km) and 1.36 TWh (if pipe length is 30 km). Respectively the share of heat produced at IRIS units (Vilnius city) also decreases and makes only 24-29% from total heat production.

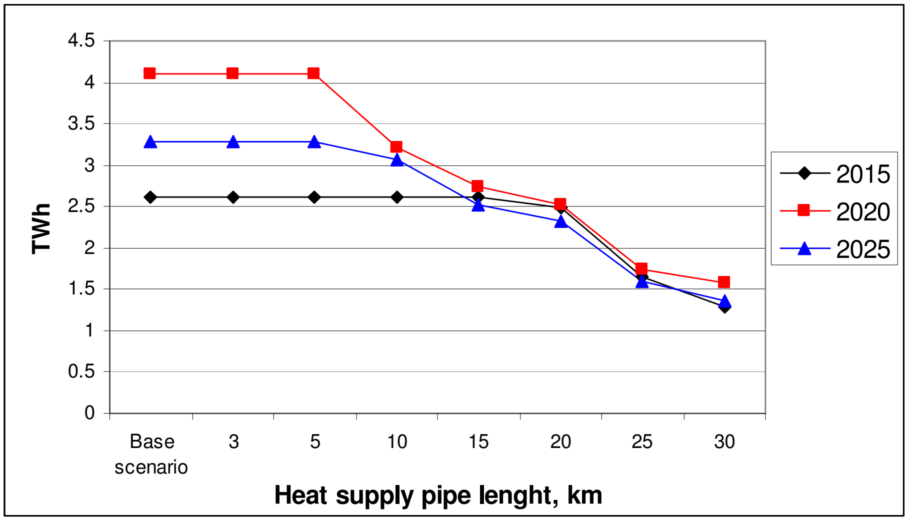


Figure 12. Heat generation at IRIS units in Vilnius

The similar situation is in Kaunas city. While the pipe length is up to 10 km, heat production is 1.64-2.2 TWh depending on the year analysed. The share of IRIS produced heat in the total heat production in Kaunas is 47-59%. If the length of pipe increases the heat production is starting to decline. For example, in year 2025 heat generation in Kaunas city is 1.89 TWh (if pipe length 15km) and 1.47 TWh (if pipe length is 30 km). Respectively the share of heat produced at IRIS units (Kaunas city) also decreases and makes only 37-47% from total heat production.

The increase of zone length makes only minor changes to the production of electricity at IRIS units. The total electricity production at IRIS units is about 5.2-5.3 TWh in year 2015 and about 8 TWh in period 2020-2025. Accordingly, it makes 37%, 49% and 45% from total electricity generation in Lithuania in 2015, 2020 and 2025.

2.3.6 IRIS electricity scenario

This scenario was calculated in order to evaluate the possibilities (looking from the economical point of view) to construct IRIS reactor only for the electricity production. Such situation could happen if the cogeneration option of IRIS could not be used. For example if there will be no possibility to construct IRIS near to the cities or heat demand in the area would be too low. In addition, this scenario could illustrate the demand for the new generating capacities in Lithuania.
Results of calculations show that in this case only two IRIS units are built. The first unit starts its operation before year 2015 and the second one before year 2020. In this case IRIS units will supply 19% from total electricity production in Lithuania in 2015, 34% in 2020 and 30% in 2025. Annual electricity production of IRIS units in this time period reaches 2.7-5.5 TWh. Electricity production in Lithuania in this case is presented in Fig. 11.

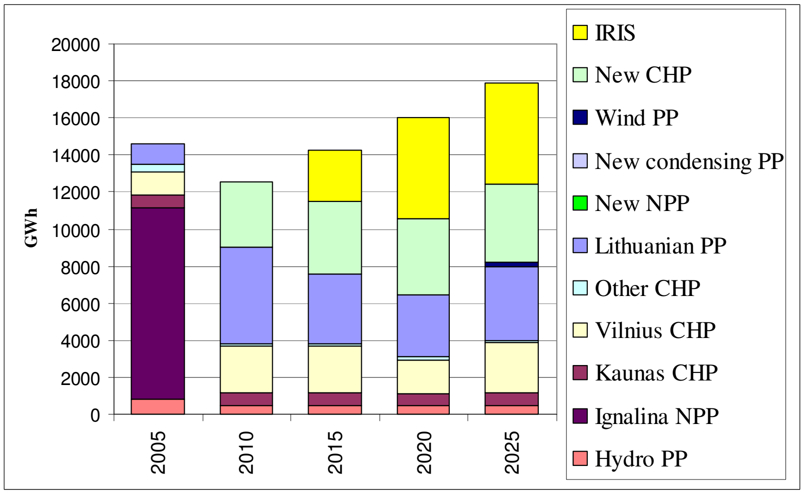


Figure 13. Dynamics of electricity production (“IRIS electricity” scenario)

Because IRIS is generating only electricity, significant part of electricity market takes existing and new CHP power plants mainly burning natural gas and biomass. They share in 2010 makes 54% while in 2015 decreases to 51% and further decreases to 43% in 2025. If compared to the base scenario (No IRIS scenario) annual electricity production in Lithuanian power plant decreased from 5.2-6.4 TWh to 3.5-4.2 TWh and makes about 21-26% from total electricity production in period 2015-2025.

3. APPROACH AND DATA FOR EVALUATION OF THE RADIATION DOSE

3.1. Permissible Radiation Doses to the Public

The main acceptance criterion for radiological accidents is to comply with the permissible doses to the public, that are defined in the basic standards for radiation protection [20]. According to these standards the permissible dose to a human body is defined as 1 mSv of the annual effective dose and for special circumstances 5 mSv of the annual effective dose.

Effective dose is defined as a summation of the tissue equivalent doses, each multiplied by the appropriate tissue weighting factor:

$$E = \sum_T w_T H_T ,$$

where H_T is the equivalent dose in tissue T and w_T is the tissue weighting factor for tissue T.

The radiation doses used in this report are the doses accumulated during the first year after the accident at the exclusion zone border (i.e. at 3 km from NPP). In the performed analysis the doses are calculated and compared with the permissible limits considering the following conservative assumptions:

- FP from the NPP compartments are released as a single puff at the height, which corresponds to the FP source to the environment;
- the worst meteorological conditions are assumed;
- the individual remains at the border of the exclusion zone infinitely (i.e. unprotected and without evacuation).

3.2. Emergency FP Release to the Environment

The first material barrier preventing the radioactive materials release is the fuel pellet. The radioactive FPs are accumulated in the fuel pellet and in the fuel-cladding gap increasing with burn-up. The main part of FP remains in the fuel pellet but some part of gaseous and volatile FP enters the fuel-cladding gap.

The release of these FPs to the environment depends on the pressure differences between the compartments and environment. The transport of the volatile FP depends not only on pressure differences but on such processes as gravitational settling or pool scrubbing as well. While entering compartments the isotopes of iodine and caesium may be in different chemical forms. Entering the compartment the most probable form of iodine is caesium iodide (CsI) and of caesium – caesium hydroxide CsOH [1, 4]. These are hygroscopic aerosols, i.e. they are soluble. The hygroscopicity of aerosols has a significant influence of the FP transport [14]. The isotopes of elemental iodine I_2 are reactive, i.e. they react with various materials of constructions and equipment that located are in compartments [1].

In case of radioactive material release to the environment in the form of aerosols and gases the human body is irradiated via the direct and indirect impact pathways. Direct impact pathways are the external irradiation by the photons and β±-particles that are present in the atmosphere and deposited on the ground. In the first case the dose is formed by the irradiation with the photons and β±-particles from the radioactive cloud, in the second case – the dose is formed by the irradiation with the photons from the isotopes deposited on the ground. The internal irradiation from the isotopes that enter human body with the inhaled air forms the so called inhalation dose and may also be attributed to the direct irradiation pathways. In these cases the individual doses are formed in the place of FP source location. The breathing rate of the human is assumed $2.67 \cdot 10^{-4}$ m^3/h.

The indirect impact pathway is the internal irradiation from the isotopes that enter human body due to nuclides migration via the food and biological chains and forms the internal irradiation via the ingestion pathway.

The above-mentioned impact ways to human body by the ionizing radiation from the radioactive FP release to the atmosphere are presented in Figure 14.

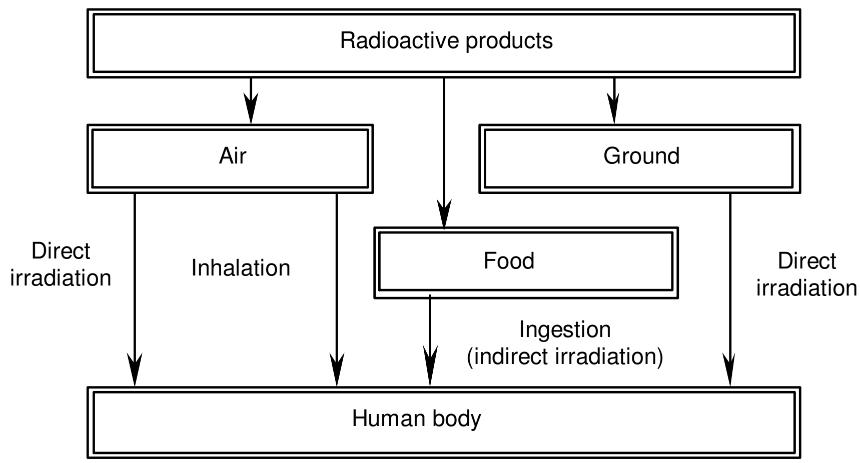


Figure 14. Impact ways to human body from the radioactive FP released to the environment

3.3. Meteorological Data for Dose Evaluation

A study to prepare meteorological data necessary for dose evaluation for one selected NPP site is based on available databases. This activity started in the first year and will continue during the second and third year, when correspondent data are updated or added.

The meteorological parameters presented in Table 8 can be applied for the dose evaluation. It should be noted, that the standard values of FP deposition and dispersion included in the calculation codes can be applied, e.g. dry deposition velocity for iodine (I_2) 0.01 m/s.

Table 8. Meteorological parameters for the analysis of FP dispersion in the environment

Atmosphere stability class	Wind speed, m/s	Inversion layer, m
A	3	1600
B	3,5	1200
C	4	800
D	5	560
E	3	320
F	2	200

Meteorology

The Lithuanian Republic is situated in the temperate climate zone. The possible new NPP site as well as whole Lithuanian territory, is located along the path dominated by western wind currents. Therefore in the global sense whole Lithuanian territory climates can be considered as homogeneous. However, on the regional scale it is rather variable, because of the prevalent intrusion of air flows from the adjacent geographical zones.

The territory of the Lithuanian Republic is divided into four climatic regions, depending on their proximity to the Baltic see, the topography of landscape and the diversity of the underlying surface. The territory of concern belongs to the East climatic sub-area. In comparison to the other Lithuanian areas, this area is marked by a big variation of air temperature over the year, the colder and longer winters with abundant snow cover, and warmer, but shorter summers. On the whole the local climate depends on the circulation of air mass from the Atlantic, but the influence of air mass from the continents of Europe and Asia continent are perceptible as well.

The most useful climatic and meteorological data are based on measurements performed by Ignalina NPP meteorological station, located approximately at a distance 5.5 km to the west of INPP site.

Air Quality and Winds

Regarding air quality, there are less pollution sources in the Ignalina NPP region than in other areas of the country, as industrial activity is not very developed and there is almost no use of fossil fuels for electricity and heating in Visaginas (apart the back-up HOB in the town). The main source of pollution comes from personal vehicles, as their average age is high; low octane fuels are also used (80, 92) together with higher ones (95, 98).

About 60 cyclones and 50 anticyclones are expected yearly due to the weather conditions of the territory concerned. Cyclones are influenced by the weather about 170 days and anticyclones about 130 days a year, because they are moving faster. During the rest of the time baric formation are observed.

Western and southern winds predominate. The strongest winds have western and south - east directions. The average annual wind speed is 3.5 m/s, and maximal (gust) speeds can reach 28 m/s. No-wind conditions are observed on the average of 6 % of the time and last no more than one day (24 hours) in the summer, and no more than two days in the winter [21].

The predominant wind direction changes depending on the distance above the ground. Beginning from the 200 m distance above ground the predominate direction is as follows: in January from south to south-west, in April from south-south-east to south-east, in October from west-north-west to north. Only during July is the predominate direction west at elevated altitudes.

In general, the wind velocity changes depending on the distance from the ground surface. At a distance of 100 m from the ground the average wind velocity doubles in comparison with wind velocities at the height of the wind vane. They grow up to distance of 500 m. On the whole the area atmospheric conditions are favorable for scattering substances from the plant ventilating stacks.

Hydro-meteorological observations in Ignalina NPP vicinities are carried out constantly. The wind velocities and directions at different heights are measured. Wind rose (Average Values for the 1997 – 2000 Period) at INPP region is presented in the following Figure.

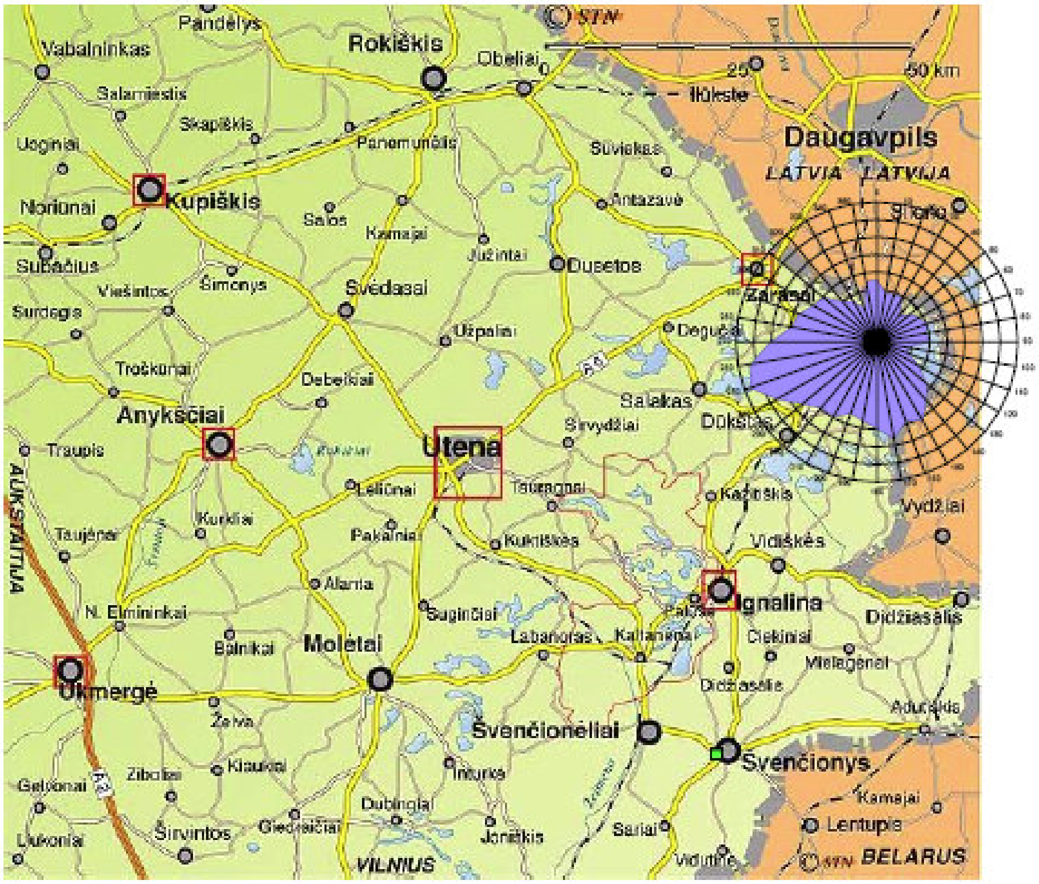


Figure 15. Wind Rose Reported on the Road Map

The season of spouts begins at the end of April and ends in the first half of September. The directions of spout motion is from south-west to north-east in 73 % of the cases. The average length of spout shift trajectory is 20 km and the length varies from 1 to 50 km. Average width of the spouts is 50 m, and it varies mostly from 10 to 300 m. Calculated maximal spout velocity with frequency one time per 10000 years is about 39 m/s.

Spouts in the vicinity of the Ignalina NPP do not exceed class F-2 according to Fujita classification [22]. Data about the most destructive spouts are incomplete. However, the following data practically can be used for calculations:

- maximal rotation speed of the spout wall is 105 m/s,
- pressure differential between center of the funnel and the fringe region of the spout is 135 kPa.

Sunshine and Temperature

Average annual duration of sunshine in the region is about 1710 hours (42 % of the maximum possible duration of the earth's surface irradiation by the sun). June is the most sunny month: the amount of sunshine in June is about 280 hours (58 % of the possible duration). The shortest period of sunshine because of cloudy weather is observed in December, which is about 20 hours (12 % of possible duration) [14].

Average annual cloudiness in region is about a force 7, and in December it increase to a force 8.5 and in May it decrease to a force 6.5. The average annual amount of cloudy days (175) is considerably larger than the clear ones.

Average annual air temperature in the region is 5.5 ^{o}C. January is the coldest month with an average monthly temperature of -6.5 ^{o}C, and June is the warmest one with 17.8 ^{o}C. Annual amplitude of average monthly temperatures is 24.1 degrees. Absolute maximum recorded temperature is 36 ^{o}C, and absolute minimum is -40 ^{o}C. The greatest oscillations of twenty-four-hour amplitude of temperature are usually in May-June, and the lowest - in December. The lowest temperature is usually observed in winter during the northern and northeast winds. In the summer the hot weather brings about the east and southeast winds.

The ground usually begins to freeze in the first part of December and lasts to the middle of April. Average depth of the frost line reaches about 50 cm, with a maximum extending to 110 cm depending on the composition of the ground and its humidity.

Precipitation and Evaporation

The atmospheric conditions are formed by circulation of air mass on the whole. Average annual amount of precipitation with correction for the moistening of the draught gauge is 638 mm. During the warm period of the year (April-October) about 70 % of all precipitation takes place, and during the cold period (November-March) - about 30 %. The coefficient of variation of multi-year annual precipitation is 0.15. Minimum of precipitation occurs in March, and the maximum - in July-August. There are about 170-180 days with precipitation (0.1 m and more) per year. The snow cover in the region is about 100-110 days per year. Average height of snow cover is 30-40 cm.

Multi-year amount of annual evaporation from the dry land is about 500 mm, evaporation from the water surface during the warm period (April-November) is about 600 mm with the coefficient of variation 0.15. Average relative humidity of air reached 80 %, and about 90 % in winter. A minimum relative humidity (53-63 %) is observed in June, and a maximum - in January.

In the Ignalina NPP area, fog is observed during the entire year. Average number of foggy days is 45 and a maximum - 62 days. Fog absorbs different impurity (noxious gases, smoke, dust) and, combined with high humidity, increases corrosion intensity, aggravating visibility and impeding transportation. Average duration of fog in the course of a month is from 4 to 29 hours and in the course of year is about 173 hours. During the cold period total duration of fog oscillates between 92 to 106 hours, and during the warm period it is about twice lower which is 49-68 hours.

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1 Appendix.
Executive Summary

LITHUANIAN ENERGY INSTITUTE
LABORATORY OF NUCLEAR INSTALLATION SAFETY

IAEA COORDINATION RESEARCH PROGRAM
"Development of Small Reactors without On-Site Refueling"

Summary of Report of the Second Working Year

Economic Benefits of Revising the Need for Relocation and Evacuation Measures Unique to NPPs for Innovative SMRs for Regions with Electricity Co-Generation

IAEA Research Contract No. LIT13092

Dr. habil. J. Augutis

27 December, 2006

This work is within the scope of activities defined within the Agency's CRP on Small Reactors with no on-site refueling. Specifically, it is relevant for Activity 2 "Definition of the scope of requirements and broader specifications to be identified for small reactors without on-site refueling" with respect to its ultimate objective (revised evacuation requirements), and to Activity 3 "Identification of requirements and broader specifications for NPPs with small reactors without on-site refueling for selected representative regions" with respect to considering specific impact on countries with colder climate and increased interest for district heating co-generation.

The ultimate objective is to establish an approach to licensing with a revised (reduced or eliminated) emergency planning requirements. Ideally, the emergency planning zone would coincide with (or be contained within) the site boundary, thus, there would be no need for off-site evacuation planning, and the NPP would become, relative to the general population, the same type of facility as any other industrial enterprise. This research will contribute toward achieving this ultimate objective, by addressing some of the relevant issues.

The aim of this work is to contribute toward the presented overall objective, using as a testbed the design of IRIS (International Reactor Innovative and Secure), as a representative innovative light-water SMR with option for infrequent on-site refueling, with the ultimate goal of developing a technology-independent approach.

For the purpose of presenting this approach, the main objectives/tasks deemed necessary to reach this final objective are listed below, however, this does not imply that all the tasks will be addresses and resolved by Lithuanian Energy Institute (LEI) alone within the correspondent project.

1. Critically evaluate current regulations to identify what changes are necessary to enable advanced licensing
2. Identify criteria based on technical, quantifiable parameters that may be used in support of the objective
3. Identify approach, based on a combination of deterministic, probabilistic, and risk management, that will enable assessment of advanced plants based on their key design operational and safety characteristics with respect to adequate emergency planning requirements
4. Prepare site-specific representative data (e.g., meteorological)
5. Perform probabilistic analyses needed to support this approach.
6. Perform deterministic / dose evaluation analyses needed to support this approach.
7. Perform a detailed evaluation of the representative reactor utilizing the combined approach.
8. Identify, discuss and quantify the benefits attainable through the implementation of this objective, i.e., licensing with reduced emergency planning requirements

LEI will contribute to the overall objective by performing research related to a subset of the above listed tasks. It is expected that other tasks will be addressed by other participants within the IAEA CRP.

Over the foreseen 3-year period, the research scope for LEI is expected to include the following objectives:

1. In Task 1, LEI will review the current licensing regulations in Lithuania and identify necessary changes. It is expected that these results, supplemented by similar results obtained within this CRP by other member countries, would contribute to ultimately defining a generic, country-independent approach.

2. Perform economic study to evaluate positive economic effect on the nuclear district heating co-generation option, due to revised siting requirements with reduced emergency planning, that would allow placement of NPPs closer to population centers.
3. Support development of justification for reduced emergency planning through PRA analyses of external events to support Contribute to activities performed by POLIMI and FER, primarily to PRA analyses.
4. Prepare meteorological data for a selected site, or several sites, that may be used within this same CRP for dose calculations, in support of the development of reduced emergency planning requirements.

During the second year, LEI performed the following tasks:

1. Review the curent licensing regulations in Lithuania, and specifically the emergency response planning for the NPP Ignalina considering technical basis (demography).
2. Analyze changes which would be necessary if the emergency planning for the future power plants in Lithuania is to be eliminated or reduced.
3. Update a study of the economic impact of revised licensing requirements on district heating. Due to climate, district heating presents a notable fraction of energy consumption in winter months, and infrastructure for its use is already in place in some population centers in Lithuania. This work will continue into the third project year, to ultimately determine potential economic benefits of revising the evacuation requirements and enabling NPP-based district heating.
4. Update meteorological data necessary for dose evaluation based on available databases.