Prospects for external sources of vehicle propulsion

results of a Delphi study

by

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I. Introduction

Abstract

This article presents the outcome of a Delphi study carried out between October 1995 and February 1996. The subject of the study is external sources of vehicle propulsion, and its possible role in achieving more sustainable modes of transportation. The Delphi study concludes that external propulsion technologies are unlikely to be the substitute for internal combustion engines. External sources of power or energy are a potentially means of saving energy, because the weight of vehicles can be reduced and energy can be produced on a large scale thus boosting efficiency. However, there is no practical system by which these advantages can be realized without putting an unacceptable strain on the quality of the transport system. The costs would be huge; there would be considerable energy losses; safety problems could arise; and the flexibility of the users is limited. Electric vehicles could, however, become important. Pantographs and quick charging techniques could become important technologies if battery technology will not improve considerably.

Why external sources of vehicle propulsion?

In 1994, the STD programme[1] developed several ideas for its need area 'transportation'. One of these was 'external propulsion', which can be achieved either by means of an external power supply (such as a cable that tows vehicles forward) or an external energy supply (such as an overhead line that provides vehicles with electricity). The premise was that the development of a power or energy supply system outside the vehicle could lead to a considerable reduction in the production of polluting emissions and contribute to a more efficient transport system:

* First, external propulsion makes possible power generation on a larger scale. In practice, this leads to higher efficiency and low emissions of harmful exhaust gases. Moreover, the emission of these gases can be restricted to non-residential areas.
* Second, the choice of primary fuel is more flexible while the sources of that fuel can be varied.
* Third, vehicles can be lighter because of the absence of the prime mover and/or energy storage. As a rule, the weight of the drive system accounts for 20-25% of total vehicle weight. In the case of electric vehicles (EVs) the drive system and energy storage can represent over 50% of total vehicle weight.

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[1] In 1993 five government departments in the Netherlands approved a research programme aimed at catalyzing sustainable technological development (STD) by:

1 convincing policy makers in government and the world of business of the necessity to develop sustainable technology, and showing them 1) how such a development can actually be undertaken, 2) how a process of innovation can be set up to that end and 3) how its effectiveness can be increased;
2. making the "pioneers in technological development" aware of the desirability of using sustainable development as a guide for R&D activities, <u>and</u> mobilizing the efforts of these "pioneers" in favor of this endeavour
3. involving "leaders of public opinion" in this process in order to prepare the way for this development <u>and</u> to introducing the public at large to the concept of sustainable technology
4. generating popular support for the development and application of sustainable technology.

The STD programme uses *illustrative processes* i.e. exemplary technological ventures that demonstrate the possibilities of more sustainable technology to a wider audience, thereby stimulating creativity and helping to build momentum in the direction of more sustainable technology.
Before such an illustrative process can be set up, the problem area must be examined and the main types of possible solutions explored. These explorations must target not only technological options and impediments, but also the socio-economic environment in which these technological options will be introduced (Vergragt/Jansen, 1993, Vergragt/van Grootveld, 1994).
In the STD programme, there are several 'need areas', such as 'housing', 'food', 'hygiene', 'transportation', etc; within these areas, projects are initiated that ultimately lead to *illustrative processes*.

* And, when in the long term fossil fuels are no longer the main energy source, energy generation on board vehicles could become far more difficult than at present.

Because of these potential benefits, external propulsion was identified by the STD programme as a highly interesting option.

<exhibit 1 here>

In May 1995, a number of Dutch experts in the area of vehicle propulsion were invited to participate in a brainstorming session. The result was a list of ideas pertaining to the propulsion of vehicles by external power or energy supply. In order to check for missing technologies, a search for patent information was carried out. On the basis of these patents and the results of the brainstorming session, a list of 14 technologies was drawn up. These technologies had to be shaped and evaluated. The Delphi method seemed to be the most interesting approach for this purpose.

Delphi method

The Delphi method is used to facilitate communication on a specific task. The method is characterized by anonymous responses, feedback to the group as a whole or to individuals, and the opportunity for respondents to modify an earlier assessment. The method is usually conducted via mail and was originally developed at the RAND Corporation by Olaf Helmer and Norman Dalkey. The main goal of the Delphi procedure is to reach consensus among a number of experts regarding the issue under investigation. The strength of Delphi is its ability to explore, coolly and objectively, issues that require a personal judgement (Gordon, 1994, Sackman, 1975, Porter, 1991).

The Delphi technique should provide more accurate judgments than those produced by techniques which involve interacting groups or individuals (Rowe et al., 1991). There are, however, certain problems and pitfalls involved in the Delphi technique (Webler et al., 1991).

* First of all, there is the selection of experts, which involves such questions as:
  - Is all relevant expertise (the various subdisciplines) represented by the group of experts?
  - What kind of expertise is needed (narrow-minded superspecialists or experts with a broad view)?
  - How can cultural bias be prevented, (e.g., by not working with a specific sub-set of experts, such as industrial experts, or experts from Asia).

Negative as well as positive correlations have been found between expertise and the accuracy of expert meanings; often experts are no more accurate than nonexperts (Woudenberg, 1991).

* Second, the degree of participation required of the experts (often extremely busy people) is often a problem. The degree of attention given to the questionnaire will depend on the amount of time the expert can spare and his/her interest in the subject matter. The dropout rate of the participants is often high (Linstone et al., 1975)
* Third, the interpretation of the responses and the results is that of the Delphi organizers. All responses are filtered through the intermediary of the Delphi organizers before they seen by anyone else (Sackman, 1975).
* And finally, the applicability and efficacy of the Delphi technique for the problem at hand must be assessed. The Delphi technique is not suitable for each and every societal problem in which long-term future uncertainties play a role. According to Webler (1991), the problems to be tackled should involve a mixture of scientific evidence and social values.

Set-up of the present Delphi study

There were several reasons why a Delphi was the appropriate method to determine whether the external propulsion of vehicles was a viable option. Alongside the general merits of the Delphi method, a number of additional arguments were taken into account:

- Only experts from the Netherlands had participated in the brainstorming session and they represented only a small fraction of world expertise in this area.

- There was a possibility that participants would be reluctant to reject a new idea proposed by a foreign guest in a face-to-face meeting.
- It was important to confront the experts with each other's arguments. If experts opinions differed on the value of certain technologies, it would be most practical to sort out the arguments by going over it again.

The questions

Often the right questions are more important than the right answers. This also applies to Delphi studies. In our case, the Delphi was aimed at clarifying:

- the expected contribution of a technology to a more sustainable transport system
- the expected period of introduction of the technology
- the nature of the main obstacles to be overcome

In designing the questionnaire for the first round, we examined a number of Delphi studies reported in the literature. These showed that it was especially important to have the experts rank their own expertise. After the questionnaire had been drawn up, it was tested in-house at TNO, after which further improvements were made.

The experts

Since motor car development is highly globalized, it was necessary to look abroad for experts to participate in the Delphi study. Moreover, to prevent bias, the experts should come from different institutional backgrounds including industry, universities, and research institutions. Therefore, we decided to aim at a panel consisting of an equal number of European, North American and East Asian experts, from various institutional backgrounds.
We did not entirely succeed in reaching the targets we had set for our expert panel. Of our 45 experts, 29 came from Europe, only 7 from North America and 9 from the Far East. Together they represented 15 different countries. Of these experts, 16 had an industrial background, 11 were with a university, and 18 were associated with governmental or independent research institutes.

response

Of the 45 questionnaires sent out for the first round, 25 were completed in such a way the answers could be processed and the outcome represented in tables. For the second round of the Delphi 25 questionnaires were sent out, 20 of which were returned. In the third round, 25 questionnaires were again sent out, 12 of which were returned. In comparison with studies from the literature, these response rates are quite good.
There were experts who, when they got a reminder call, were frankly skeptical of external propulsion technologies. For example, one expert sent a fax in which he refused to participate in the project because

> *"after discussing the idea with our experts on electric drive systems we envisage a number of technical problems involved in the realization of your proposals, especially in passenger cars with the exception of flywheels in hybrid drive systems. Because we feel that there will be no economical solutions available in the near future, we would rather not participate in your study"*.

We had asked the panelists to complete all the questions, even if they did not consider themselves experts. However, many questions were left open. It was clear from the comments, and occasionally from the phone conversation, that a perceived lack of expertise was the main reason that some questions were not answered.

Profile of the respondents

Of the 45 experts who were approached, 25 filled out a questionnaire.

<exhibit 2 here>

In general, we were satisfied with the response rate just over 50 %. However, it should be noted that the response from North American and industrial experts was lower. In the case of industrial experts, this might be due to the general skepticism towards external propulsion technology, evinced by these experts. Among those employed in industry there is apparently less scope to consider technologies that break with tradition than in universities or other research organizations. It was interesting that all the respondents who mentioned their professional training had a degree in engineering. Of the 25 respondents, 23 had some degree of supervisory responsibility; four were even responsible for their entire organization.

<exhibit 3 here>

Although many respondents had a supervisory position, they had not lost their contact with research and technology:

<exhibit 4>

Our respondents were all male, which probably reflects the enormous underrepresentation of women in engineering.

We concluded that our respondents form a somewhat homogeneous group. Their profile might read: a middle-aged man with an engineering degree, who has been relatively successful in his profession, but has not lost touch with the actual nuts and bolts of vehicle/propulsion technology.

II. Results: general views on external vehicle propulsion

Expertise

There was considerable variation in the panelists' level of expertise on the various technologies (figure 1)

<exhibit 5 here>

What was surprising was the fact that 60 % or more of the panelists had no expertise in 9 of the 14 technologies listed. Of the remaining 5 technologies, at least 60% of the panel did have some expertise. This striking difference in the level of expertise reflects the choice we made at the time the expert panel was selected. As noted above, we believe that the judgment of this panel is relevant, even though they have no expert knowledge of a number of technologies. In our conclusion we will elaborate on this point.

Sustainable technologies

The main question which concerned us was what external propulsion technologies could be used to realize a more sustainable transport system. The results are given in figure 2.

<exhibit 6 here>

Because of the differences in expertise, we decided to compare the assessments of the entire panel with those of the panelists who claimed to have a degree of expertise in the field.

On the basis of figures 2 and 3, we concluded that the panelists' level of expertise did not did not play a significant role in their assessments. This is not to say that anyone would give the same answers: although the expertise of the panel differed considerably on various technologies, they probably belong to a global community of vehicle propulsion technologists, who hold roughly the same views on developments relevant to their field of technology. It is even possible that panelist who do not claim to be experts on a specific technology but still belong to the 'expert community' provide a 'sounder' assessment because they were not hindered by the 'love of a technologist for his creation'.

<exhibit 7 here>

Technologies of interest

As is clear from figures 2 and 3, technologies 1, 2, 3 and 9 are seen as the most promising ones for more sustainable vehicle propulsion. Therefore, the results of the Delphi which pertain to these technologies will be further analyzed. Technologies 8 and 14 were ridiculed by some panelists. Since practically no one believed that they were possible, they were not part of the second Delphi round.

On the basis of the results of the first round, we decided to split technology 6 into linear electric engine for public transport (6a), and linear electric engine for private transport (6b). The results of these two technologies are given in the next chapter.

In the light of the comments of our experts, we decided to analyze the technologies 1, 2, 3, 6, and 9 most thoroughly, to disregard 8 and 14, and to try to create more consensus on the other technologies, for example by putting explicit questions to panelists with rather extreme positions. The results are presented in Chapter III.

Even after the second round, there was no consensus on two clusters of technologies - namely, technologies 4, 5 and 13 (involving the transmission of energy to vehicles by electromagnetic waves) and technologies 10, 11 and 12 (involving the transmission of momentum by means of differences in air pressure) There were two reasons for this failure two obtain a consensus:

- A few panelists did not exercise care when they completed or revised their questionnaires. As the number of panelists was relatively small, this resulted in a somewhat indeterminate picture. For example, one respondent who filled out all "**c**"s on one page.
- Some panelists took a more positive view of specific technologies because they did not assess them as we had requested, i.e., as a technology for vehicle propulsion on a fairly large scale. For example, one panelist gave a very positive assessment of conveyor belts and towing lines but added: *'of course, not for vehicles, but to transport people, say, from parking lots to downtown areas'*.

Suggestions for other external propulsion technologies

Several suggestions were made for other technologies that might be considered. A number of these were concerned with electric vehicles (EVs). Supercapacitors were suggested as a means of absorbing peak discharge and recharge currents. In that way batteries could be discharged at close to the design rate. The use of ultralight materials was suggested as a way to reduce electricity consumption. Several panelists mentioned fuel cells for energy storage, and others suggested hybrid cars with greatly improved internal combustion engines (Otto or Stirling).

It was suggested that attention should also be given to other alternative fuels (biomass-derived or LNG), improved railways and other public transport facilities, changes to the tax system, etc. There was only one suggestion for a kind of propulsion that could be seen as 'external' namely using the potential energy of the vehicle by placing vehicle stops above the level of the road way. This idea might interest road builders, as making junctions higher could conserve some energy that is otherwise lost during braking. However, it could only be used on a fairly small scale.

The suggestions of the experts contributed to our impression that the panel did prefer the EV technologies that we had suggested, but not as technologies for external propulsion. The fact that so many of them mentioned hybrid cars, or technologies that improved the EV by improving the energy source within it, points to a strong preference for EVs that are entirely internally propelled. Therefore, in the second round we added questions on the general attitude towards external propulsion.

Further discussion of the general views of the panel

The results of the first Delphi round led us to believe that the panel was skeptical about the general concept of external propulsion. Therefore, our second Delphi round contained a question on their overall views on <u>external</u> propulsion technology.

<exhibit 8 here>

One of the answers given by a panelist in the first round suggested that if after EVs and hybrid cars were introduced on a large scale, it might then become more easy to introduce technologies to transmit electric energy to driving vehicles. In that way, local emissions could be further reduced and the maximum range of EVs extended. So we asked the panel:

> * Do you think that new internal propulsion systems, such as internal combustion engine/electric hybrids and fuel cells, can play a role in the transition process from today's vehicles to vehicles driven by an external power or energy source?

The reactions of the panel varied considerably: Some panelists had not understood our intention. Most agreed that after the introduction of EVs, technologies to transmit electricity to driving vehicles might be introduced successfully. However, a considerable number of panelists emphasized that the need for flexibility would make this impossible. Moreover, some of them argued, in the future there will be fuel cells and improved batteries, and thus no need for these technologies which involve large investments. It was even argued that no one is interested in promoting these technologies; industry in any case, has no plans in that direction.

Therefore, if batteries and fuel cells do improve, there will probably be no need for external propulsion. However, if these technologies do not meet expectations, there is one external propulsion technology that could become viable in the future: external electricity transmission to moving vehicles. As our panel has made clear, pantographs (probably overhead, but perhaps in some other form if safety problems can be solved) are the preferred technology.

We decided to reformulate these findings and present them to the panel in a third round. This extra round would also enable us to compare these findings with quite different technologies (such as Stirling engines powered by biomass-derived fuel, as was suggested by one panelist), which might lead to more sustainable modes of transportation. These conclusions appear in Chapter IV.

III. Results: analysis of prospects and problems related to the most promising external propulsion technologies

Electric vehicles (1, 2, 3, 9)

On the basis of the general views on the various modes of vehicle propulsion put forward during the first round, the following technologies were selected for reconsideration by the respondents:
- Electric Vehicles (EVs) where possible coupled to a grid (technology 1)
- EVs with flywheel, recharged at stops (technology 2)
- EVs with batteries, recharged at stops (technology 3)
- Solar cells on the vehicle itself (technology 9)

We will first examine the qualitative comments of the panel on these technologies, and then analyze the quantitative data. The panel's general comments were as follows:

1. Electric vehicles coupled to an electricity net (for example, by means of overhead lines) for longer distances along main roads, and combined with a battery for local trips.

The basic idea is seen as highly promising, because it would enable electric vehicles to travel longer distances. The main obstacle is the infrastructure, which is considered too complicated and too expensive for niche markets. On the other hand, if the market exceeded the niche, it would be difficult to meet peak load demand. Furthermore, the limits to mobility make this technology more suitable for large vehicles, such as buses and trucks than for private cars. It appears to be something of a utopian dream, except for vehicles that are rail-connected.

Due to the low energy prices, there is no economic pressure to improve the present system of goods transport. It might be more logical to consider improvements to the existing railway system. But here the costs would be higher than those involved in developing the batteries that would make such systems unnecessary. Other problems mentioned were visual pollution (above-ground cables), the battery technology, and the organization of access to the network.

2. Electric vehicles with a high-speed flywheel, which make use of fast recharging at certain points (e.g., stops or crossroads).

It was pointed out there have been some commercial realizations of this technology (Oerlikon bus, Parry tram, NMVB Gent ±1950) but only with low-speed flywheels. Problems arose when the buses got stuck in traffic and could not reach a charging point in time. Nevertheless, the technology might be an option for urban buses and city taxis.

The development of low-weight flywheels at a reasonable cost is, however a problem, and no reliable technology is yet available. The flywheels would be expensive, due to the sophisticated production processes, and the same holds true for the bearings and the vacuum pumping system which would be required.
Some panelists questioned the technical advantages of using flywheels: high, since comparable power can be delivered by a number of modern battery technologies. Only the power in/out efficiency of flywheels is better than that of batteries. The infrastructure for recharging is even more sophisticated than for EVs with batteries and thus expensive.

3. Technology based on the same principle as in 2, but equipped with a battery instead of a flywheel.

This technology has been somewhat more successful than 2, having been used by the German Railways (Akkutriebwagen). The trial was ultimately suspended when it proved to be expensive, and did not meet functional requirements.
The recharge time, energy storage capacity, battery weight, and range are all problems which must be looked into. Although this solution would be cheaper than technology 2, it would still be expensive; the high cost of a sophisticated battery system remains a major obstacle in the development of a battery-powered EV. Another aspect mentioned was the fact that the life span of the battery would be reduced due to the high charging power.

9. Solar cells on the vehicle itself. The vehicle is equipped with a battery, so that solar energy can be stored during daylight hours.

The power density of panels mounted on the vehicle cannot generate a significant portion of the energy that is required for driving (up to 100 W/m2). Therefore, it would make no sense to mount solar cells directly on passenger vehicles.
While the use of renewable energy is a major goal, this should be done in the most cost-effective way. This means that panels should be exposed to sunlight for as long as possible, i.e., not on a vehicle which would often be parked in the shade. Moreover, solar cells have a longer life span than cars, which makes them more suitable for use on houses. In the future, there may be limited

advances in some applications (air conditioning during parking), and certain geographical regions.

Figure 4 shows the frequency distribution of the assessments of the technologies 1, 2, 3, and 9 with respect to environmental sustainability.

<exhibit 9 here>

The frequency distribution is almost identical to that recorded during the first round. EVs with batteries (3) make the greatest contribution to environmental sustainability, directly followed by vehicles coupled to an electricity net (1) and vehicles equipped with solar cells. EVs with a flywheel (4) were not thought to make any real contribution to sustainability. The above ranking becomes clearer when we exclude those experts with no special expertise in these fields (figure 5).

<exhibit 10 here>

Figures 6 and 7, show the expected feasibility of these technologies on a laboratory and commercial scale.

<exhibit 11 here>

<exhibit 12 here>

Here, too the distribution of responses is nearly the same as during the first round. Approximately 80 % of the respondents believed that technologies 1, 2 and 3 could be realized within 10 years. In the case of vehicles with solar cells (9) there was more variation in the assessments, but 64 % of the respondents felt that this technology could be realized within a decade.

When it came to realization on a commercial scale, about 75 % of the experts saw 2010 as the probable horizon for vehicles equipped with batteries (3) or coupled to an electricity net (1). For the vehicles with a flywheel (2) or solar cells (9) the horizon was estimated at 2020 and 2030 respectively.

Figure 8 shows the frequency distribution of the main obstacles to the realization of the technologies.

<exhibit 13 here>

Approximately 40% of the respondents mentioned cost as a major obstacle to the realization of all the technologies. In the case of EVs with flywheel (2) and solar cells mounted on the vehicle (4) the technology itself was seen as a major obstacle.

It is interesting that 20% of the respondents saw organizational problems as an obstacle in the case vehicles coupled to an electricity net (1).

In round 2, we asked the panel to examine more closely the technologies 1, 2, and 3, on the basis of two open questions:

* Which potential techniques for the disconnectable transmission of electric energy to moving private vehicles (e.g. overhead pantograph, side pantograph, etc.) do you consider the most promising?
* Which potential techniques for intermittent energy transmission to vehicles at stops (from every 100 meters up to several kilometers) are most promising? (e.g., overhead charging, induction charging, etc.)

On the first question, many experts expressed doubts as to whether this would be a workable technology for private vehicles. Of the 20 panelists who returned their second round questionnaire, 4 left this question open; this was interpreted as a negative answer, since all these experts took a negative view of external propulsion in general. Four panelists explicitly stated that they had no faith in any of these technologies. The main issue for almost all the panelists was safety, and most people who did express a preference for a specific technology (8 panelists) preferred overhead pantographs. Three panelists expressed a preference for side pantographs, but two of them indicated that they were concerned about safety. One panelist preferred power lines *'in ground if safety aspects can be overcome, otherwise overhead'*. One advantage of side pantographs or 'in ground lines' is that variations in vehicle height are not a problem.

<exhibit 14 here>

In the case of technologies for intermittent energy transmission to vehicles, the same general doubts about practicality were expressed by the panelists. Most of them expressed a strong preference for induction charging, on the grounds that this technology was the most user-friendly. However, induction charging results in energy loss, and for this reason some panelists preferred overhead charging by means of direct connection. Some panelists suggested overhead charging might be used for trucks and buses, and induction charging for passenger cars.

<exhibit 15 here>

Two additional questions on solar cells mounted on vehicles were triggered by remarks made during the first round:

> * Solar cells on vehicles are occasionally mentioned as a potential alternative. However, the current power density of solar cells (max. ~0.5kW per vehicle) cannot supply enough energy to run a conventional car.
>
> - Do you think solar cells might be used in future as the main source of power for cars?yes/no
>
> If so, by what sort of technological innovations might this be accomplished?
>
> - Could you mention other applications of solar cells that could be used in the vehicle of the future?

The vast majority (18) were of the opinion that solar cells could not be used as the main power source for cars. The two panelists who answered 'yes' to the first question both added a significant proviso: if batteries can be improved (both power density and efficiency). Almost all panelists considered solar cells a viable option for auxiliary functions: cooling cars parked in the sun, feeding various electronic systems, etc. Moreover, solar cells could be used to extend the range of EVs. However, several panelist felt that solar cells would be too expensive, and could only be considered an option if the price were to come down considerably. One panelist said that solar cells could be an important option, but that they should not be mounted on cars, since solar cells last much longer than passenger cars. Moreover, the surface area of the car is limited, and in any case is not ideally suited for the reception of solar energy.

Linear engine

The general view on technology 6, the linear electric engine, was somewhat negative; the positive views were largely confined to public transport. For this reason, the following distinction was made in the second round:

6a Linear electric engine for public transport,
6b Linear electric engine for private transport.

The frequency distribution of the estimated environmental sustainability of the linear electric engine (6) in general, and for public and private transport (6a and 6b) is shown in figure 9.

<exhibit 16 here>

The panel estimated that the contribution to sustainability, in case of linear engines for public transport, would be twice as high as in the case of private transport. The difference was due mainly to the panelists' view that this technology was applicable for railways, but was not inefficient for vehicle applications.

This conviction is further underlined in figures 10 and 11, which shows the expectations with regard to realization. The majority (52%) of the experts said that pilot schemes to test this technology are already under way, e.g., the magnetic floating system for the Linear Shinkansen of Japan Railways.

Most experts (74%) believe that the commercial realization of the linear electric engine for public purposes will be a reality by 2010, while 54% believe this will happen even before then. Commercial applications for private transport appear to be further away: according to 38 % of the experts, this will not be practicable before 2020. Some 31 % do not believe that this technology will ever be realized.

<exhibit 17 here>

<exhibit 18 here>

The main obstacles to realization are cost (± 40%) and technology (± 20 %) (see figure 12). Other specific barriers mentioned are safety and spatial problems related to the realization of the infrastructure required for public transport.

<exhibit 19 here>

Conclusions with regard to the most promising external propulsion technologies

The results of our analysis of the most promising technologies for the external propulsion of vehicles are clear and unambiguous; The technologies seen as most promising were selected because:

- they are closely related to internal propulsion technologies, which were preferred
- they are suitable for public rather than private transport
- they are suitable for very specific applications, rather than general use.

We will elaborate on this general conclusion in the next chapter.

IV. General conclusions on the future development of technologies for external propulsion of vehicles

In the third round we asked the panel to comment on the following general conclusions:

General conclusions on the future development of external propulsion of vehicles.

If the internal combustion engine as a source of power for the propulsion of vehicles is ever replaced by a new and more environmentally sound technology, then technologies that use an external source of power or energy are unlikely to be the substitute. External sources of power or energy are a potentially means of saving energy, because the weight of vehicles can be reduced and energy can be produced on a large scale thus boosting efficiency. However, there is no practical system by which these advantages can be realized without putting an unacceptable strain on the quality of the transport system. The costs of an extensive infrastructure would be huge; there would be considerable energy losses within the infrastructure; safety problems could arise; and the flexibility of the users is limited.

EVs may in a sense be considered 'externally propelled' because their energy has been converted in large-scale, efficient power plants. Alongside improved internal combustion engines, battery-powered electric engines and hybrids will be the main power sources for the car of the future. In the short term, there will be no scope for external propulsion technology, at least not on a large scale.

On a limited scale, however external propulsion technologies could play a role in urban areas, e.g., to transport people by conveyor belts or cable cars. However, these systems will operate as public transportation systems and not as systems that facilitate transport by private vehicles. Moreover, these technologies are intended to reduce traffic and parking problems, especially in downtown areas, and it is not clear whether they also reduce environmental pollution.

In the long run, it remains doubtful whether externally powered vehicles will play a role in sustainable private transport. If EVs do capture a substantial market share, the development of battery technology (capacity, efficiency, life span in cycles, etc.) will be of great importance. If battery performance can then be substantially improved, the external propulsion of vehicles will be redundant because there would be no substantial energy gain while flexibility would be reduced. If battery performance remains the major problem posed by EVs, technologies to supply energy to moving vehicles could become important as a means of extending the range of EVs. This cannot be accomplished by means of electro-magnetic radiation, due mainly to low efficiencies and safety problems. Pantographs will be the preferred technology, probably overhead pantographs, in the light of safety considerations. Direct current enables people to return energy to the grid. The disadvantage of this technology is that the various heights of vehicles may present problems, while the overhead power lines will form an unaesthetic element in the landscape. However, pantographs will not take over the complete energy supply of vehicles; they will have their own energy source, so that overhead lines will only be needed on specific sections of the road.
Another technology that may become important for EVs is quick charging at stops. Expert opinions differ somewhat on this issue. Because of safety problems and driver convenience, induction charging is preferred by many experts. However, this results in a reduction in efficiency and for this reason, many others prefer direct charging, by means of overhead connections.

Systems which combine internal and external propulsion will probably be introduced first in large metropolitan areas.

Solar cells mounted on the vehicle, could be used to supply additional energy, they could power various auxiliaries like air conditioning, heating, and electronic devices while the vehicle is parked. The usefulness of solar cells in extending the range of EVs is restricted, due to the limited amount of power that can be generated on the surface of the car. In the future, solar cells which are not mounted on vehicles may be a more promising source of sustainable energy.

The comments of the panelists on these conclusions

Of the twelve panelists who completed the third questionnaire, six responded to our general conclusions. One panelist felt that these conclusions should have been formulated even more negatively, since we had not taken into account the fact that an increasing number of households now own more than one car. This means that households could have an EV for short distances and an internal combustion engine vehicle (ICEV) for long trips. As a result, there would be no need for external propulsion on long-distance motorways. Three panelists said that by and large the conclusions reflected their personal views. We will deal with two comments of a more general nature in the following chapter.

V. Other technologies for sustainable transportation

With regard to our main conclusion, one panelist stated that a change in mentality is needed: people should give up their private cars; public transport should be promoted; and the feasibility of such schemes as multi-user cars that could be rented at short notice should be looked into. This view is particularly interesting in the light of the comments of three other panelists, who focused on the extra questions in the third round. As one panelist stated:

> (....) *'The questions assume that equal range (of vehicles) is necessary. It is not! In most households in the USA and in an increasing number elsewhere in the OECD, 2+ cars are owned. (....) Most of these households are willing to accept one limited range vehicle, with little compensation. In fact, many view home recharging as so desirable, that they prefer cars with limited range (160 km) and home recharging over comparable gasoline cars.'*

And according to another:

> *'An EV will not replace a normal car with the same technical performance. (...) You cannot compare apples with pears. (...) EVs with double costs are on the market.'*

These panelists seem to be saying that changes in transport technology will always be accompanied by, or even be completely intertwined with, social changes. Technological forecasting therefore makes little sense: to the extent that technological developments can be foreseen, it is never clear beforehand which of the developments will actually be realized. The need for new transport technologies is currently changing under the influence of technological developments themselves, as well as various other changes in society. In innovation studies the term 'socio-technical change' is often used to describe the interactive process by which technologies and social behavior interact and develop. This implies that there is in fact no way to forecast with any certainty which technologies will require social changes. The best way to gain useful insight is probably social simulation or social experiment. Social experiments might trigger learning processes, social learning for the users of vehicles as well as for technologists working on vehicles (Elzen/Mulder, 1995).

In the light of these remarks, the answers to the questions on internal propulsion technologies are not surprising. Some panelists probably opted for a compromise between the required performance characteristics of the technology and the characteristics actually demanded by the public.

An EV which offers about the same performance as current family cars in terms of range, speed, number of passengers, etc., <u>at about the same cost per kilometer</u>, will be possible within:

<exhibit 20 here>

An EV which offers about the same performance as current family cars, in terms of range, speed, number of passengers, etc., <u>at about double the cost per kilometer</u>, will be possible within:

<exhibit 21 here>

An ICEV that uses biomass-derived fuel and offers about the same performance as current family cars in terms of range, speed, number of passengers, etc., at about the same cost per kilometer, will be possible within:

<exhibit 22 here>

> One panelist estimated that biomass-derived fuel would not be used in ICEVs, but predicted that within 10 years it would be used to generate electricity for EVs. Another panelist said that he assumed that this would be possible within 20 years if:
> - there were no tax on biomass-derived fuels
> - fossil fuel prices went up

An ICEV that uses biomass-derived fuel and offers the same performance as current family cars in terms of range, speed, number of passengers, etc., at about double the cost per kilometer, will be possible within:

<exhibit 23 here>

> One panelist estimated that biomass-derived fuel would not be used in ICEVs, but predicted that within 5 years it would be used to generate electricity for EVs.

A vehicle which is powered by some other kind of sustainable energy (e.g., hydrogen generated by solar energy), and offers about the same performance as current family cars in terms of range, speed, number of passengers, etc., at about the same cost per kilometer, will be possible within:

> Six panelists did not believe there was any technology that could achieve this. Five panelists mentioned fuel cells which use hydrogen generated by solar energy and estimated that these could be realized in 20/20/30/30/50 years. One panelist predicted that biomass could be used to fuel gas turbines and Stirling engines within 30 years.

A vehicle which is powered by some other kind of sustainable energy (e.g., hydrogen generated by solar energy), and which offers about the same performance as current family cars in terms of range, speed, number of passengers, etc., at about double the cost per kilometer, will be possible within:

> Four experts doubted whether this could ever be achieved, while seven others estimated that would become possible within 10/10/15/20/20/30/40/40 years. One panelist estimated that biomass could be used to fuel gas turbines and Stirling engines within 10 years.

Suggestions for further study

In the course of the project, several panelists remarked somewhat facetiously that what we were aiming for already existed, in the form of electric railways. Although we cannot foresee all the implications at this moment, it might be worthwhile to start at the other end by asking ourselves whether the use of electric railway lines could be optimized by admitting private vehicles onto the tracks. This would probably involve external automated control of the vehicle, or coupling to trains. In all probability, the implications of such a development would be enormous. However, it is impossible to say under what - if any - circumstances this idea could be feasible. In any case, our Delphi panel is not the appropriate body to predict the consequences of such a development.
A second subject for further study might be the possibilities of battery technology. Although many of our experts considered this technology crucial to the future of the car, they differed considerably

on the possibilities that might emerge. An extensive evaluation of the potential energy efficiency and cost of batteries could be extremely valuable when the time comes to take decisions on our future transport system.

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exhibit 1

Technologies:

1. Vehicles, where possible coupled to an electricity net. Electric vehicles, coupled to an electricity net (e.g. overhead lines) to travel longer distances along main roads, combined with a battery for local traffic.

2. Electric vehicles with flywheel, recharged at stops. Electric vehicles with a high speed flywheel, that uses fast recharging at certain points (e.g. stops or crossroads).

3. Electric vehicles with battery, recharged at stops. The same principal as 2, but then equipped with a battery instead of a flywheel.

4. Energy transmission by means of micro-waves. Wireless electric energy transmission for moving vehicles, by means of micro-waves.

5. Energy transmission by means of short wave radiation. Wireless electric energy transmission by means of high energetic short wave radiation.

6. Linear electric engine. A transportation system where the vehicle is rotor, and the track is stator in a linear electric motor.

7. Towing-line for vehicles. Towing-line that can be coupled to individual vehicles, that also can drive separately.

8. Conveyor-belt. Conveyor-belt on which individual vehicles can be transported.

9. Solar cells on the vehicle. Power generating by solar cells on the vehicle itself. The vehicle will be equipped with a battery, so that solar energy can be can be stored all day.

10. Tunnels with forced air flow. The use of smooth-wall tunnels with a forced air flow, with the same speed as the vehicles, so that the drag resistance is zero.

11. Tunnels with forced air flow at high speed. The use of smooth-wall tunnels with a forced air flow, with a high speed that pushes the vehicles forwards.

12. Tunnels with vacuum at the end. The use of tunnels with a vacuum at the end that propels the vehicles through the pressure drop.

13. Power transmission by laser. A laser pointing at a vehicle, where on somehow a reaction-engine can provide power.

14. Waving road-surface. A waving road-surface that pushes vehicles forward on a wave.

exhibit 2

	number of experts approached	questionnaires returned
Europe	29	17
North America	7	2
Far East	9	6
industrial background	16	4
university Background	11	8
government agency or research organization	18	13
Total	45	25

exhibit 3

persons supervised	number of respondents
0	2
<10	9
10-100	8
>100	2

exhibit 4

profession:	number of respondents:
researcher	13
designer	1
production engineer	1
marketeer	1
planner	4
executive	6
other	3

(some mentioned more than 1 profession)

exhibit 5

Technologies:

1.Vehicles, where possible coupled to an electricity net.
2.Electric vehicles with flywheel, recharged at stops.
3.Electric vehicles with battery, recharged at stops.
4.Energy transmission by means of micro-waves.
5.Energy transmission by means of short wave radiation.
6.Linear electric engine.
7.Towing-line for vehicles.
8.Conveyor-belt.
9.Solar cells on the vehicle.
10.Tunnels with forced air flow.
11.Tunnels with forced air flow at high speed.
12.Tunnels with vacuum at the end.
13.Power transmission by laser.
14.Waving road-surface.

Expertise levels were explained as follows:

a. major: you are a specialist/expert on the subject
b. average: you have some primary knowledge (i.e., you have read a lot on this subject and/or done minor research)
c. minor: you have secondary knowledge (i.e., you have read about this technology in technical/scientific literature, you discussed it with colleagues)
d. no special expertise: you know about as much on this subject as any educated newspaper reader.

figure 1: Personal expertise regarding the technologies

(Note: We know from the various comments that if a question did not trigger any response, this was generally a sign that the expert did not posses any expertise on the subject).

exhibit 6

Technologies:

1.Vehicles, where possible coupled to an electricity net
2.Electric vehicles with flywheel, recharged at stops
3.Electric vehicles with battery, recharged at stops
4.Energy transmission by means of micro-waves
5.Energy transmission by means of short wave radiation
6.Linear electric engine
7.Towing-line for vehicles
8.Conveyor-belt
9.Solar cells on the vehicle
10.Tunnels with forced air flow
11.Tunnels with forced air flow at high speed
12.Tunnels with vacuum at the end
13.Power transmission by laser
14.Waving road-surface

Environmental Sustainability was explained as follows:

a. major: might contribute to the solution of a global environmental problem that threatens human existence
b. average: might lessen global environmental problems or solve regional environmental problems
c. minor: will only lead to a reduction in local environmental problems
d. none: will solve no problems, or else create more problems than it solves

figure 2: Importance of technologies for environmental sustainability

exhibit 7

Technologies:

1.Vehicles, where possible coupled to an electricity net
2.Electric vehicles with flywheel, recharged at stops
3.Electric vehicles with battery, recharged at stops
4.Energy transmission by means of micro-waves
5.Energy transmission by means of short wave radiation
6.Linear electric engine
7.Towing-line for vehicles
8.Conveyor-belt
9.Solar cells on the vehicle
10.Tunnels with forced air flow
11.Tunnels with forced air flow at high speed
12.Tunnels with vacuum at the end
13.Power transmission by laser
14.Waving road-surface
Environmental sustainability was explained as follows:

a. major: might contribute to the solution of a global environmental problem that threatens human existence
b. average: might lessen global environmental problems or solve regional environmental problems
c. minor: will lead to a reduction in local environmental problems
d. none: will solve no problems, or else create more problems than it solves

figure 3: Assessments of panelists with special expertise with regard to the importance of technologies for environmental sustainability

exhibit 8

	number of panelists
negative	10
perhaps in specific areas	3
perhaps some specific technologies	4
no answer	3

exhibit 9

Technologies:

1.Vehicles, where possible coupled to an electricity net.
2.Electric vehicles with flywheel, recharged at stops.
3.Electric vehicles with battery, recharged at stops.
9.Solar cells on the vehicle.
Environmental Sustainability was explained as follows:

a. major; it might contribute to the solution of a global environmental problem that threatens human existence
b. average; it might lessen global environmental problems or solve regional environmental problems
c. minor; it will only lessen local environmental problems
d. none, it will solve no problems, or create more problems than it solves

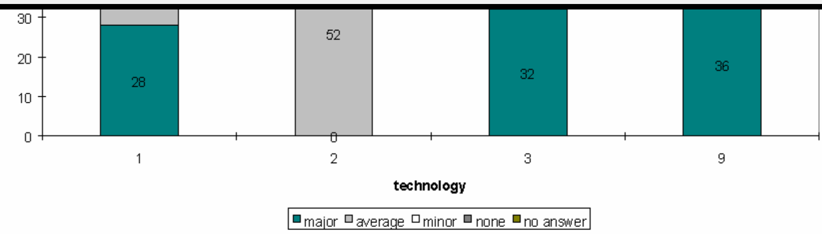

figure 4: importance for environmental sustainability of technologies 1, 2, 3 and 9

exhibit 10

Technologies:

1.Vehicles, where possible coupled to an electricity net.
2.Electric vehicles with flywheel, recharged at stops.
3.Electric vehicles with battery, recharged at stops.
9.Solar cells on the vehicle.
Environmental Sustainability was explained as follows:

a. major; it might contribute to the solution of a global environmental problem that threatens human existence
b. average; it might lessen global environmental problems or solve regional environmental problems
c. minor; it will only lessen local environmental problems
d. none, it will solve no problems, or create more problems than it solves

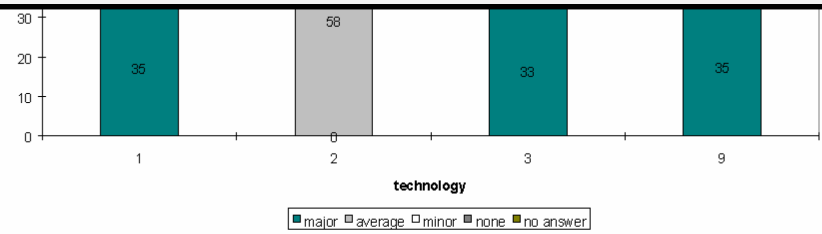

figure 5, Assessments of panelists with expertise in technologies 1, 2, 3, and 9 with special reference to environmental sustainability

exhibit 11

Technologies:

1.Vehicles, where possible coupled to an electricity net.
2.Electric vehicles with flywheel, recharged at stops.
3.Electric vehicles with battery, recharged at stops.
9.Solar cells on the vehicle.

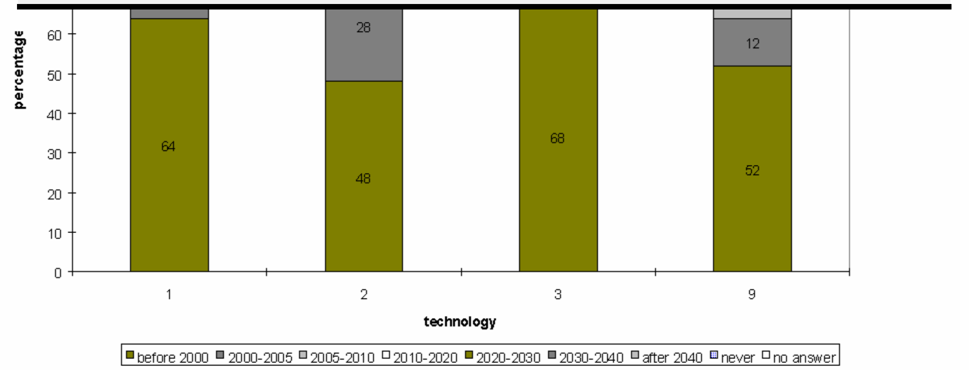

figure 6: Expected feasibility of technologies 1, 2, 3, and 9 on a laboratory scale

exhibit 12

Technologies:

1.Vehicles, where possible coupled to an electricity net.
2.Electric vehicles with flywheel, recharged at stops.
3.Electric vehicles with battery, recharged at stops.
9.Solar cells on the vehicle.

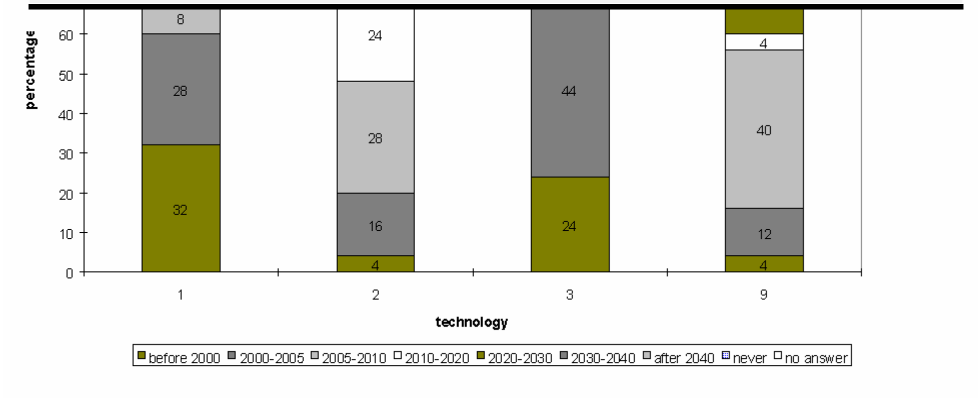

figure 7: Expected feasibility of technologies 1, 2, 3, and 9 on a commercial scale

exhibit 13

Technologies:

1.Vehicles, where possible coupled to an electricity net.
2.Electric vehicles with flywheel, recharged at stops.
3.Electric vehicles with battery, recharged at stops.
9.Solar cells on the vehicle.

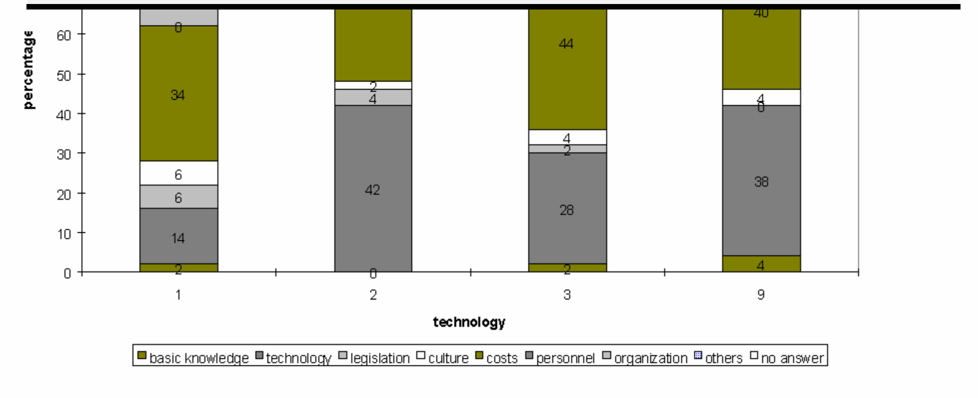

figure 8: Main obstacles to the realization of technologies 1, 2, 3, and 9

exhibit 14

ELECTRICITY TRANSMISSION TO MOVING VEHICLES

	number of panelists
overhead pantograph	8
side pantograph	3
in-ground	1
none	4
no answer	4

exhibit 15

ELECTRICITY TRANSMISSION AT STOPS

	number of panelists
induction charging	11
direct overhead charging	3
battery replacement	1
no intermittent charging	1
no answer	4

exhibit 16

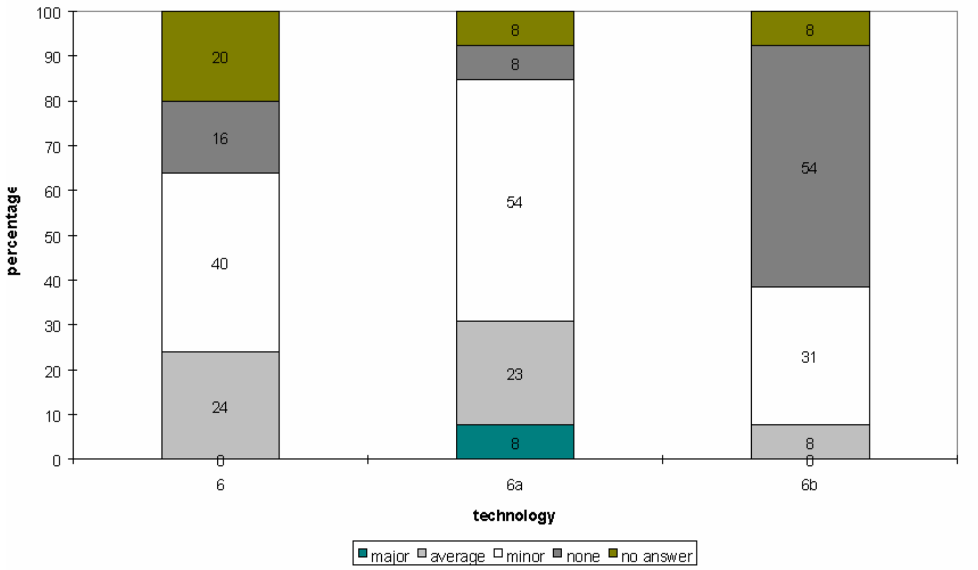

figure 9: Importance for environmental sustainability of technology 6 (linear engine), 6a (public) and 6b (private)

exhibit 17

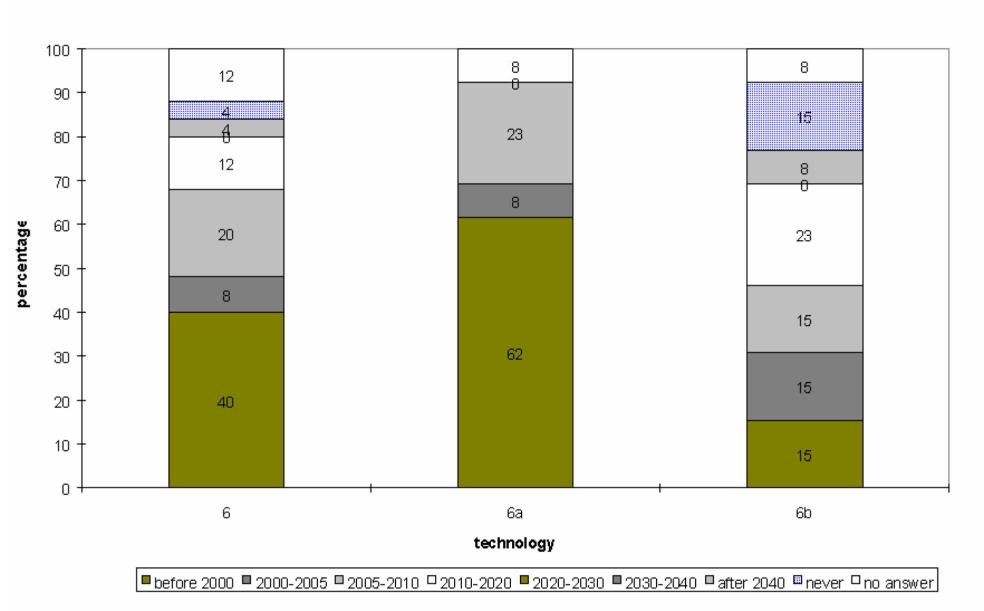

figure 10: Expectations with regard to the realization of technologies 6, 6a and 6b on a laboratory scale.

exhibit 18

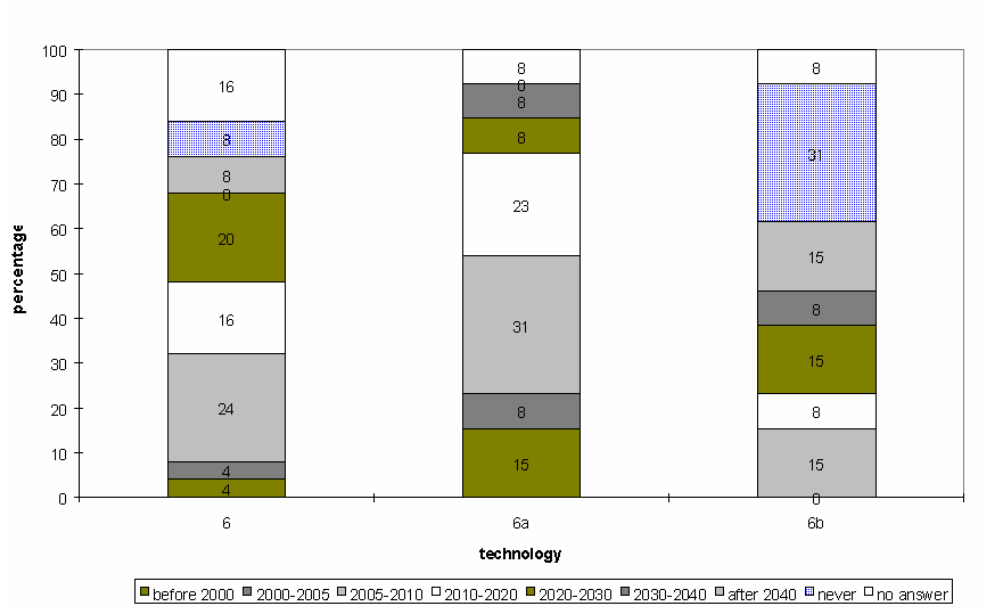

figure 11: Expected realization of technologies 6, 6a and 6b on a commercial scale.

exhibit 19

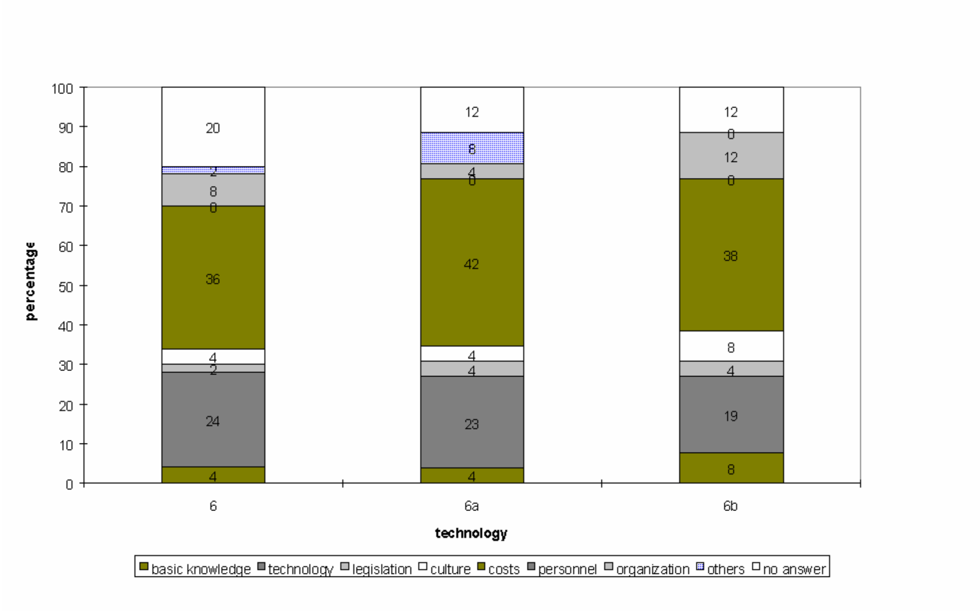

figure 12: Main obstacles to the realization of technologies 6, 6a and 6b

exhibit 20

years	number of panelists
5	
10	
15	1
20	1
30	2
40	1
50	
never	7

exhibit 21

years	number of panelists
5	
10	3
15	
20	2
30	
40	
50	3
never	4

exhibit 22

years	number of panelists
5	
10	1
15	1
20	6
30	
40	
50	
never	2

exhibit 23

years	number of panelists
5	3
10	3
15	2
20	
30	
40	
50	1
never	1