So far we discussed the physical dimension of the *zero-emission mobility system* of the future. As you now understand, the future mobility system will not only require electric vehicles. It will also require substantial change in the electric power system. Now, lean back and think for a moment. Imagine that you know all physical components in the future power and mobility system. Would you be able to predict how the system behaves? The engineering professionals among you may be disappointed to admit that you cannot. Even if you knew the millions of components in the system, and their technical specifications, you cannot know how and when exactly each consumer uses the electricity consumption devices in his home, in the office and on the road. Evidently, there is more to *system behavior* than just physical components and technical specifications. It is also about *user behavior*, which brings us to the social dimension of the system.

Actors

The *system components* in the social dimension of the system are known as *actors*. Actors may be individual consumers, like you and me, they may be established organizational entities like private companies and governmental bodies, or they may be ad hoc organizations formed to serve specific interests. Actors making investment and disinvestment decisions will determine if and how the power and mobility system evolves. Actors producing and using electricity will determine if and how the future power system can be balanced. In turn, governmental agencies, regulatory bodies and system operators may design incentives to influence investment and consumer behavior. However, while governments may be designing policies to incentivize consumers to buy electric vehicles, established engine and car manufacturers may be pursuing different propositions for consumers, such as

more efficient and cleaner combustion engines. In other words, there are many interactions between actors in the system. These interactions are *non-linear*, as actors in the system are *reflective*: they learn and adapt. Even if we know all the individual actors, we cannot predict the whole system's behavior.

Complex adaptive systems

Such systems are known as *complex adaptive systems*. The complexity stems from the *dynamic interactions* between the components, with feedback loops among actors, across subsystems and time scales, implying that we cannot predict the behavior of the aggregate system from our understanding of the individual actors and the physical system components. The behavior of the aggregate system is an *emergent property* of the system: its behavior evolves from the actions and interactions between the actors, between the physical components, and between the social and technical subsystems. The interactions may involve information exchange, financial transactions, power flows, and so on. The actors are *autonomous decision making agents*, and they are *heterogeneous*. They are heterogeneous, for example, in the sense that they do not have the same information, they do not pursue the same goals, they do not have the same means to enforce their agenda, they may be willing to take risks or be risk aversive, they may be competitive or willing to collaborate, and so forth. The learning and adaptive behavior of the actors implies that the aggregate system is also adaptive. *Micro-events* in the system or changes in the economic, social and physical environment thus induce the system to change and exhibit new and unforeseen system behavior. At the same time, complex adaptive systems exhibit *path*

dependencies, implying that the system behavior is also determined by the system's history. Think, for example, of capital investment decisions made in the past.

Figure: Ant colony, an example of a complex adaptive system

Complex adaptive systems are all around us: examples are the climate system, urban systems and ecosystems, and at lower system levels you can see animal swarms, insect colonies and our own bodies as complex adaptive systems. Both the power system and the mobility system can be characterized as complex adaptive systems. Both are characterized by physical networks extending across a variety of geographical scales and jurisdictions, and by networks of heterogeneous actors using, operating and managing these networks, and providing technologies

and services. Analytically, you can distinguish between the physical and social dimension, but in practice, these are different sides of the same coin: you cannot isolate the social from the physical dimension of the system. We are dealing with complex adaptive *socio-technical* systems.

The mobility system

The current mobility system is intricately *intertwined* with the fossil energy system, as it largely depends on fossil fuels. According to the US Energy Information Administration, in 2016, nearly three quarters of the total petroleum consumption in the US was in the transportation sector, and mind you, the US petroleum consumption equals more than 20% of the world oil consumption.

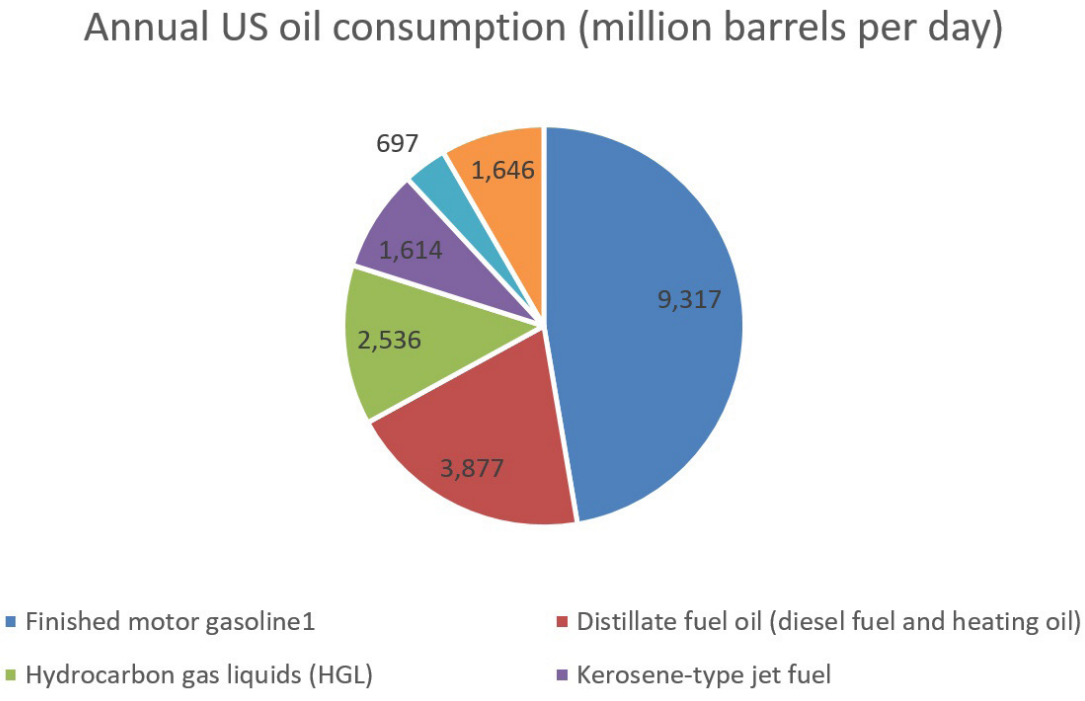


Figure: Annual US oil consumption. Source: US energy Information Administration

Electric cars: Policy

Lecture notes: Lecture 1.4

Vehicle manufacturers and oil companies, and their suppliers, established a mobility system that revolves around petroleum derived fuels. While electric vehicles are already entering the market in increasing numbers, old cars still need to be refueled with gasoline and diesel, and most people are still buying gasoline and diesel fueled cars rather than electric vehicles. In view of the capital invested, the established industrial base, refueling infrastructure and vehicle park cannot be replaced overnight. Historic investment decisions as well as social routines have created *path dependencies* hindering the mobility system to easily switch to a zero-emission electric mobility system. The new system requires *new physical components*, both in the mobility system and in the energy system, to bring the zero-emission mobility system into being, and it requires established actors to reconsider their roles and new actors to take on new roles.

While Tesla is a new car manufacturer dedicated to electric vehicles, established car manufacturers are still improving the fuel efficiency of their combustion engine cars, while at the same time producing hybrid and all-electric cars. Battery electric cars will be competing with fuel cell electric cars and with combustion engine cars designed for hydrogen combustion. While recharging infrastructure for electric cars is taking shape, we also see hydrogen refueling infrastructure evolving and we see biogas and biodiesel refueling infrastructure being installed to service traditional combustion engine cars. In some of these cases, established actors are taking the lead. In others, new actors are entering the stage.

For electric vehicles, recharging infrastructure is an important enabler, and with the need for smart charging, a new type of actor is entering the market, the so-called

aggregator. The aggregator links the electric power and mobility system for the benefit of both: by shifting demand to times when electricity is cheap, especially when renewable energy is abundantly available, the aggregator helps to avoid overload of the electricity distribution network during peak demand and to reduce recharging costs for the electric vehicle owner.

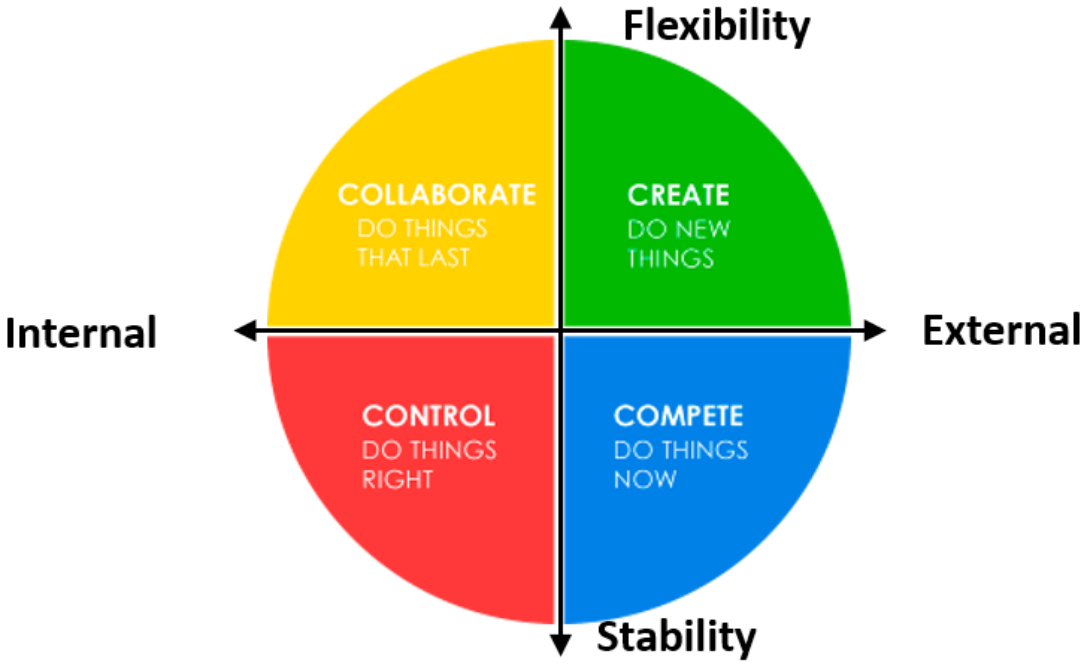
New roles

Let us dive a bit deeper into the social dimension of the system in which electric vehicles are claiming their role. We already discussed that the power and mobility system is a complex adaptive system in which many different actors play a role. On the one side, we are dealing with established industries and infrastructure providers, on the other side, new actors are entering the stage, such as dedicated electric vehicle manufacturers, and we see new actors adopting new roles, such as aggregators. Consumers are obviously important actors too, and governments play an important role. This course is too short to give you a comprehensive overview of all relevant actors. The important message here for you is to understand that the *values and goals of all these different actors may not be aligned*. To understand this phenomenon we introduce the notion of *competing values*.

Competing values framework

The competing values framework builds along two axes to identify the different types of values actors might have. The first axis is the one that classifies actors on the basis of their flexibility or preference for stability. The second axis identifies actors based upon how internally or externally oriented they are. These axes make four different quadrants. In the top right corner are those actors that are flexible

and externally oriented, this is the so-called *'create' profile*. These are actors that do not feel bound by regulations and try to innovate radically. In the bottom left corner are organizations that are quite opposite and whose values thus compete.



The bottom left quadrant is the *'control' quadrant*. For the organizations situated in the control quadrant risk is not an option. They have a strong preference for maintaining the status quo, and to that end they employ all control options at their disposal. Another example of competing values is that between those actors in the lower right corner, the so-called 'compete' quadrant, and in the upper left the 'collaborate' quadrant. While the competitors are short term focused on private gains, the collaborators are more externally focused, and ready to establish collaborative coalitions with other actors which share their values and are willing to cooperate towards a shared higher goal. Sustainable development largely builds on the latter type of actors.

Experiments

In designing effective policy interventions for complex adaptive systems, governments may decide to set-up experiments and pilots, so that they can learn which interventions are more effective. In the Netherlands and many other countries, a variety of local experiments has been set-up with smart grids and smart charging of electric vehicles. For such experiments, coalitions of actors have to be established, which are *most easily* recruited from the create and collaborator quadrants, and less easily from the control and compete quadrants. Setting up a *'coalition of the willing'* is challenging, as it will involve actors from the public as well as the private sector, which goals and values are not naturally aligned. Another challenge is that experiments rarely fit within the established rules and regulations, so that exemptions may be needed from current legislation.